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# TRACKING OF TROPICAL CYCLONES



**U. S. NAVY WEATHER RESEARCH FACILITY**  
**BUILDING R-48, U. S. NAVAL AIR STATION**  
**NORFOLK 11, VIRGINIA**

**JULY 1963**

## FOREWORD

This report was written under contract with the Navy by the Florida State University, Tallahassee, Florida for Navy Weather Research Facility Task 12, "Improved Hurricane and Typhoon Forecasting Techniques."

The main emphasis of this work is on identifying, locating, and tracking the tropical storm center and deals with the operations aspects involved in such a task. Some of the problems in charting the tracks, measuring the degree of accuracy of various fixes along the tracks, and of irregularities in the tracks of tropical cyclones are discussed and compared.

Dr. Charles L. Jordan of Florida State University planned the approach to this subject, investigated the problems involved, and wrote this report. Acknowledgement is made to the members of Airborne Early Warning Squadron Four (VW-4) for their assistance in gathering information for this study. Mr. Harold A. Corzine, leader of Task 12, co-ordinated the details of aligning the aims of this report with the objectives of Task 12 and reviewed the format of the manuscript prior to the final edit. Mr. John M. Mercer performed the final edit of this report for the Navy Weather Research Facility.

This publication has been reviewed and approved on July 24, 1963 by the undersigned.



CHARLES A. PALMER, JR.  
Commander, U. S. Navy  
Officer in Charge  
U. S. Navy Weather Research Facility

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## 1. INTRODUCTION

In the Northern Hemispheric portions of the Atlantic and western Pacific Oceans the geographical positions of tropical cyclones, during most of their life history, are now determined primarily by observations from reconnaissance aircraft. Observations from islands and ships are very helpful in indicating the presence of tropical cyclones, but only in rare cases are the routine surface observations of much help in positioning the storm centers with the accuracy which is now expected from the forecasting centers. This is because there are relatively few ship observations in the vicinity of the storm centers and the number decreases with improvements in the accuracy of the forecasts and in the effectiveness of the warnings.

In other geographical areas where tropical cyclones occur (including portions of the Indian Ocean, the western South Pacific, and the eastern North Pacific) observations from reconnaissance aircraft are rarely available. In these areas the ship and island reports assume a more important role in tracking tropical cyclones, but the reported storm positions are subject to considerably larger errors than those in the areas where aircraft reconnaissance is normally available.

The tracking of tropical cyclones becomes somewhat easier as the storms approach land areas. At such times radar observations become of primary importance in many parts of the world, and surface observations are plentiful enough to provide considerable assistance in many cases.

Numerous satellite observations of tropical cyclones have been made in recent years. Al-

though there is little hope that the storm positions provided by observations of this type will approach the accuracy normally provided by aircraft reconnaissance observations, such data should be of considerable help in tracking storms over the vast oceanic regions where other types of observations are almost entirely lacking.

This report is aimed at describing and evaluating the various types of data which are used in tracking tropical cyclones. Information of this type should be helpful in the systematic use of the available data in tracking these storms on a current basis as well as in evaluating the accuracy of the storm tracks obtained by postanalysis. Some of the topics treated have some bearing on the problem of the ultimate limit of accuracy which can be expected in tracking tropical cyclones and in predicting their future motion. However, prediction techniques and procedures, as such, will not be discussed in the report.

The tracking of tropical cyclones will be considered from several aspects in this report. The problems of identifying and locating the storm center from various types of observations will be treated first. The operational aspects of tracking the storm center will then be discussed, along with considerations of the accuracy of the observations and the limitations of the track of the storm center as an indicator of the motion of the storm as a whole. Procedures and techniques used in aircraft reconnaissance of tropical cyclones will be discussed in some detail and the utility and limitations of observations obtained by other means, including radar and satellites, will be considered.

## 2. IDENTIFYING AND LOCATING THE STORM CENTER

### 2.1 The "Center Fix"

The center of an atmospheric disturbance can be identified in several ways, depending on the type of observations available. For extratropical cyclones primary emphasis is ordinarily placed on the pressure distribution and, accordingly, the point of lowest pressure is considered as the storm center; although for some purposes it might be more appropriate to identify the center with the "point" of zero wind speed. Relatively little attention has been given to this problem in extratropical meteorology since no attempt is made to locate or forecast the center positions of extratropical cyclones with the same degree of precision which is attempted for tropical cyclones. This difference in emphasis arises because of basic differences in the structure of these two types of cyclonic systems.

The area of bad weather and strong winds in the extratropical cyclone is not concentrated

nearly to the degree that is usually observed in the intense tropical cyclone. Therefore, relatively large errors in locating the center position lead to only minor differences in the weather and wind conditions which would be forecast for a given geographical location. In contrast, track differences of as little as 25 miles<sup>1</sup> may be extremely important in the damage at a given geographical location due to a hurricane or typhoon. Because of the extreme concentration of the heavy precipitation and strong winds near the center of the tropical cyclone, there is a great effort made to track the storm center as accurately as possible. Individual observations of the center position, as determined by reconnaissance aircraft, radar, and by other means, are commonly referred to as "center fixes". The reconnaissance missions are planned in most cases to provide this type of data as close in time as possible to that of the regular 6-hourly hurricane and typhoon advisories.

<sup>1</sup>The nautical mile is used as the basic unit of distance throughout the report, unless otherwise indicated.

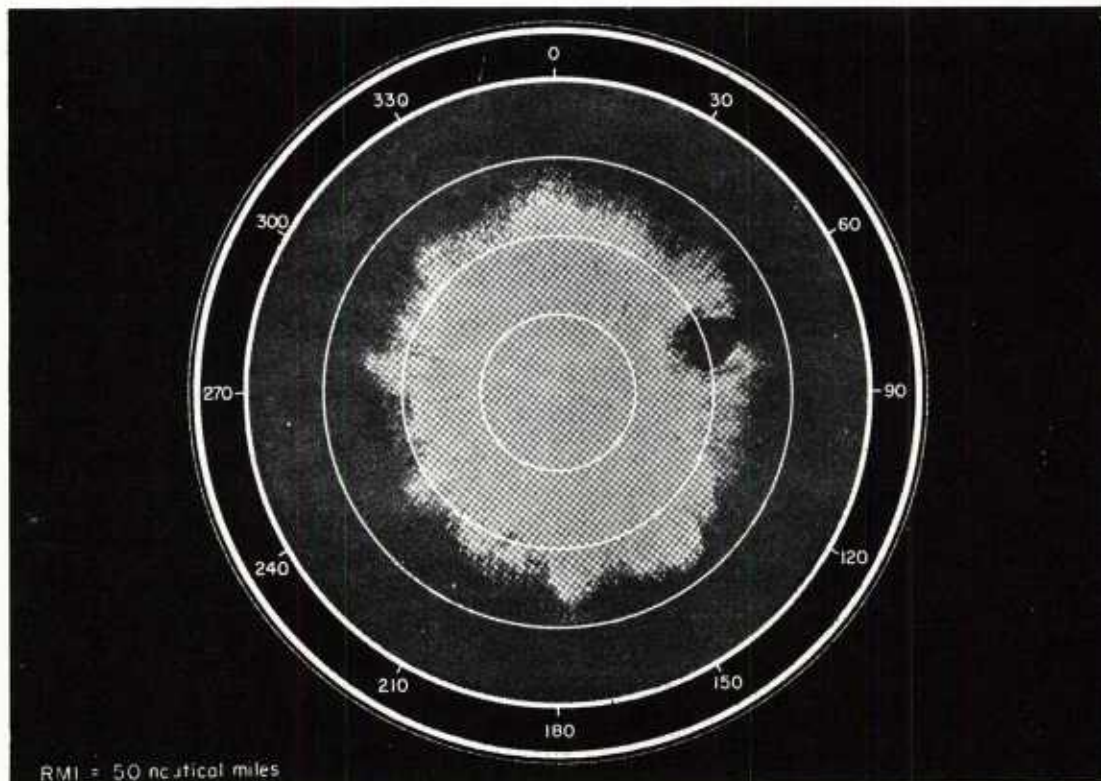


Figure 2.1. An Illustration of the "Hole in the Sea Clutter" which is often apparent from airborne radar at the wind center of a hurricane. This pattern can be best observed from levels above 5,000 feet with the antenna tilted down slightly. (From [37].)

### 2.1.1 Definitions of the Storm Center

The organization of the tropical cyclone is such that the storm center can be defined in several ways. The center can be located by the wind and pressure fields, but in most cases the area of reduced cloudiness and weaker winds, known as the eye of the storm, provides a more convenient means of locating the storm center. An eye is present in all well-developed tropical cyclones of hurricane intensity, and the heaviest and strongest winds tend to be found just outside the eye in a well-organized and fairly symmetrical pattern corresponding to the so-called "wall cloud". The size of the eye varies over a rather large range with reported diameters varying from a few miles to more than 60 miles. Although the eye occasionally appears to be elliptical, or even irregular, in shape; the geometrical center of the eye is probably the most meaningful way of identifying the center of a tropical cyclone. As discussed below, the center of the eye is usually determined from the radar presentation rather than from visual observations. This is preferable in most cases since there may be considerable amounts of relatively inactive cloud matter at some levels within the eye which would tend to make it difficult to locate the center of the eye by visual means.

There has been a tendency among the reconnaissance observers to speak of several types of "eyes," including the "pressure eye," the "cloud eye," the "wind eye," the "radar eye," and the "circulation eye." The "wind eye" is often located from observations of the effects of the wind on the state of the sea, or perhaps from variations in the character of the radar return from the sea (see fig. 2.1) while the "circulation eye" is determined visually from the organized pattern of the stratocumulus within the eye (see fig. 2.2 and 2.3). The use of the word "eye" is somewhat awkward in these descriptions and it would seem preferable to speak of the "wind center," "pressure center," "radar center," and "cloud circulation center." In the following discussion this latter terminology will be followed except for the "radar center." This point is considered as the most practical means of identifying the storm center and, unless otherwise indicated, "storm center" will be synonymous with "radar center."

In the ideal case the center of the storm -- as identified by the point of lowest pressure, the point of zero wind speed, and the center of the eye as seen visually -- would coincide with the geometrical center of a strong ring-like radar echo associated with the wall cloud of the

storm. However, the detailed observations collected in Atlantic hurricanes in recent years by the National Hurricane Research Project suggest that these centers are seldom coincident. Pressure gradients are often weak within the eye and the point of lowest pressure is often displaced from the geometrical center of the eye. There are also cases when more than one center of low pressure can be found within the eye. The same problems arise in considering the singularity in the wind speed field; i.e., the "point" of zero wind, since in most cases there is a close relationship between the pressure field and the wind field.

The displacement of the wind center from the pressure center, or from the radar center, would seldom exceed 10 miles except possibly in cases of very large eyes and in very rapidly moving storms [27]. However, relatively small differences are often important in computing the velocity of the storm center from "fixes" made a few hours apart. As discussed in later sections, "fixes" made by reconnaissance aircraft at intervals less than a few hours are of very little value in determining storm motion because of errors in the aircraft position and difficulties in identifying the exact storm center.

### 2.1.2 Vertical Displacement of the Centers

The wall cloud of a well-developed tropical cyclone is usually almost vertical and extends throughout most of the troposphere [20]. For practical purposes the center of the storm can, therefore, be considered to be at the same geographical position at all altitudes. However, detailed observations of the wind and pressure distributions within the eye at various levels would probably show some variation with height in the location of the "wind center" and "pressure center". It is also likely that these positions would show some variability with time.

It is difficult to specify any one level or layer to be given priority in locating the wind or pressure centers. The vertical extent of the storm is dependent upon intensity and storms which are not of hurricane intensity may not be easily detected from observations made at upper troposphere levels. The operational forecasters would probably place greater confidence in observations made at the 700-mb. level or lower, but observations at the higher levels may be just as useful in locating the wind and pressure centers in well-developed tropical cyclones. In fact, there is some evidence to suggest that multiple pressure and wind centers within the



Figure 2.2. Curved Lines of Stratocumulus in the Edge of the Eye of Hurricane CONNIE on 7 August 1955 as Observed from the 700-mb. Level. Note the Curvature of the Lines and the Suggestion of a Center off the Left Side of the Photograph.



Figure 2.3. Cloud Patterns in the Eye of Hurricane CONNIE on 9 August 1955 as Observed from the 500-mb. Level. The Apparent Center of the Pattern Was Near the Right Edge of the Photograph. The Eye Was about 60 Miles Across at the 500-mb. Level at this Time and the Apparent Center in the Cloud Pattern Was about 10 to 15 Miles from the Northeast Wall Cloud.

eye are less likely to occur at middle troposphere levels than at levels near the surface.

The previous discussion in regard to the choice of levels is largely academic since the center position is usually determined from radar observations rather than from wind or pressure observations. The radar beam of the airborne sets used in hurricane reconnaissance is usually quite broad in the vertical and, with the exception of observations made in or near the eye, the radar presentation of the wall cloud results from the integrated effect of hydrometeors distributed throughout a very deep layer. For example, if the aircraft is more than 50 miles from the center, the portion of the wall cloud illuminated by the beam, as defined in the standard way [3], would exceed 30,000 feet in depth. Principal contributions to the radar return would be expected from the lower levels where the liquid water content is normally greatest. Thinner layers are viewed by the radar at closer ranges and differences in eye size can be detected in some cases by varying the tilt of the antenna while flying in or near the eye [22]. The eye tends to be somewhat larger at the upper levels and small changes in the center position with height have been noted. These differences are not always present and do not show any consistent pattern when they do occur. There is, therefore, little justification for considering any systematic tilt of the eye, or wall cloud system, with height.

## 2.2 Utilization of Aircraft Reconnaissance Observations

Hurricanes in the Atlantic and typhoons in the western Pacific are tracked over the open oceans mainly by data provided by reconnaissance aircraft. In this section some of the difficulties of locating the storm center by this means will be considered with the assumption that the aircraft position is accurately known at all times. The additional problem of errors in the aircraft position will be considered in a later section.

### 2.2.1 Radar Center

As indicated previously, the storm center can usually be best identified by means of radar observations. The heavy precipitation in the wall cloud surrounding the eye of tropical cyclones occurs in well-defined patterns and often leads to definitive radar presentations of the type shown in figures 2.4 - 2.9. In some cases the wall clouds appear as isolated, ring-like echoes (figs. 2.4 - 2.6), and in other cases spi-

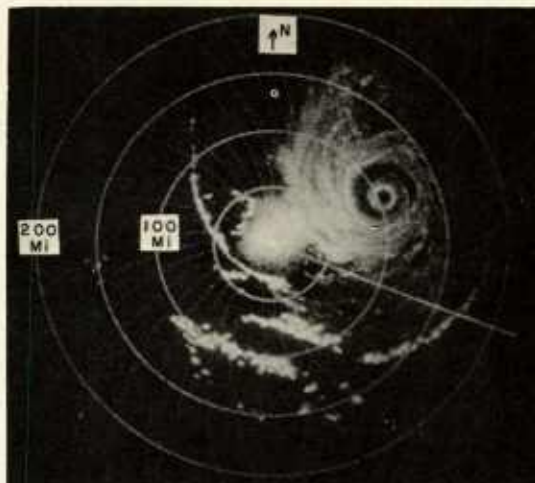


Figure 2.4. A Radar Presentation of Hurricane DONNA Taken at Approximately 2100 GMT, 6 September 1960 from the APS-20E Radar of a U.S. Navy C-121 (WV-3) Aircraft. The Aircraft Position, at the Center of the Photograph, Was about 10 Miles South of Grand Turk Island. (From [21].)

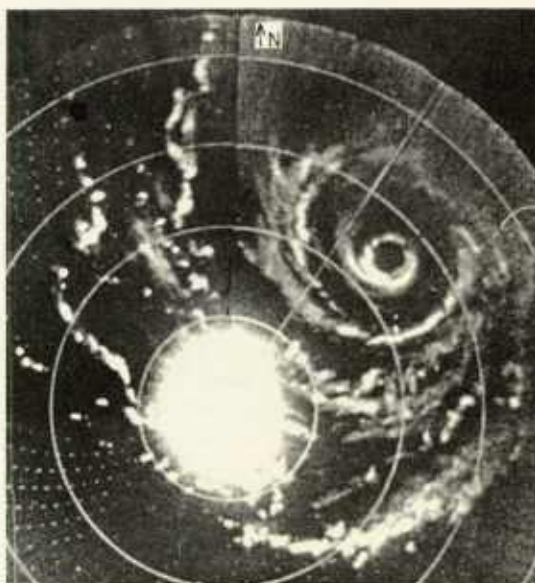


Figure 2.5. A Radar Presentation of Hurricane ESTHER Taken at 1602 GMT, 16 September 1961 from the APS-20E Radar of a U.S. Navy C-121 (WV-3) Aircraft. The Range Markers Are at 50 Nautical Mile Intervals. At the Time of this Photograph the Storm Center Was Located about 400 Miles Northeast of San Juan, Puerto Rico. (Official Photograph, U.S. Navy.)

ralling convective bands tend to merge to form the eye wall (figs. 2.7 - 2.9). The cloudiness is highly variable within the eye but is primarily stratiform in character and is seldom detected by the radar. The intense echo due to the wall cloud may not form a ring and an open sector of the type illustrated in figure 2.10 may be present. In cases of this type and in other situations during developing hurricanes, such as shown in figures 2.11 and 2.12, the exact position of the center of the storm is difficult to specify from the radar presentation. The same lack of definition in the radar patterns is often present in the weakening stage of tropical cyclones and during their transformation into extratropical storms.

The photographs shown in figures 2.4 - 2.12, except for figure 2.9, were taken from the APS-20E radar which is carried by the WV-3 aircraft<sup>1</sup> of the U. S. Navy reconnaissance squadrons. This radar gives a much better presentation of tropical cyclones than that provided by other types of radars currently in use on weather reconnaissance aircraft. The APS-20E is a high-powered set (peak power 2,000 kilowatts), the resolution is relatively great (the antenna beam is relatively narrow) and the set operates at a wavelength (10 cm.) where precipitation attenuation of the radar energy is relatively weak. Most airborne radars operate near the 3-centimeter wavelength and have much lower power outputs and larger antenna beams than the APS-20E, with the result that the presentations never approach those shown in figures 2.4 - 2.8. These poorer presentations provide some detail over a limited area and are extremely helpful in the locating of the storm center after the aircraft is within 50 miles or so of the center, but they do not offer the long-range tracking potential provided by the APS-20E. Precipitation attenuation effects are often very marked at the 3-centimeter wavelength, as illustrated by figure 2.13. In order to use radar data of this type it has been necessary to develop techniques for estimating the location of the storm center from radar data covering only a portion of the storm. Since these techniques are used more by land stations, they will be discussed in the section covering the utilization of land based radar.

The photographs presented in figures 2.4 - 2.8 represent some of the most definitive radar presentations obtained during hundreds of hours

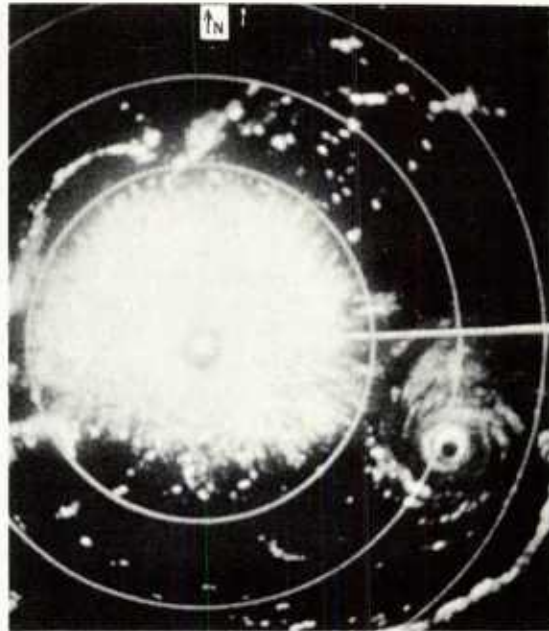


Figure 2.6. A Radar Presentation of Hurricane DAISY Taken at 0312 GMT, 28 August 1958 from the APS-20E Radar of a U. S. Navy C-121 (WV-3) Aircraft. The Range Circles Are at 50 Nautical Mile Intervals. The Bright Area within 100 Miles of the Center Is Primarily "Sea Clutter" which Arises from Return from the Rough Seas. Some of the Prominent Echoes in the Northwest Sector at Ranges of 100 to 150 Miles Are from the North Carolina Coast. (Official Photograph, U. S. Navy.)

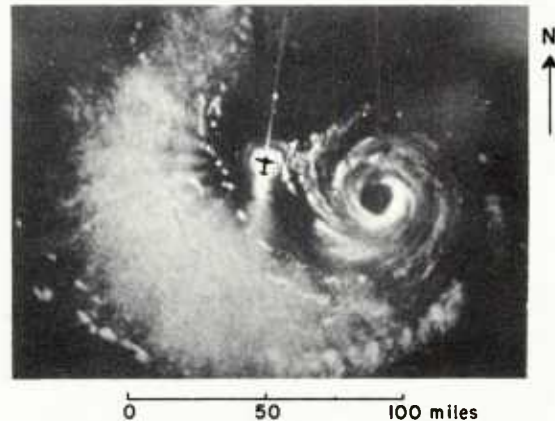


Figure 2.7. A Radar Presentation of Hurricane DAISY Taken at 1511 GMT, 27 August 1958 from the APS-20E Radar of a U. S. Navy C-121 (WV-3) Aircraft. The Storm at the Time of this Photograph Was Located about 300 Miles East-Southeast of Jacksonville, Fla. (From [ 20].)

<sup>1</sup> New Navy designator for WV aircraft is C-121.



Figure 2.8. A Radar Presentation of Hurricane ABBY Taken on the Morning of July 15, 1960 from the APS-20E Radar of a U.S. Navy C-121 (WV-3) Aircraft. Range Markers Are at 50 Nautical Mile Intervals. At the Time of this Photograph the Storm Was Approaching the Coast of British Honduras. (From [ 8].)

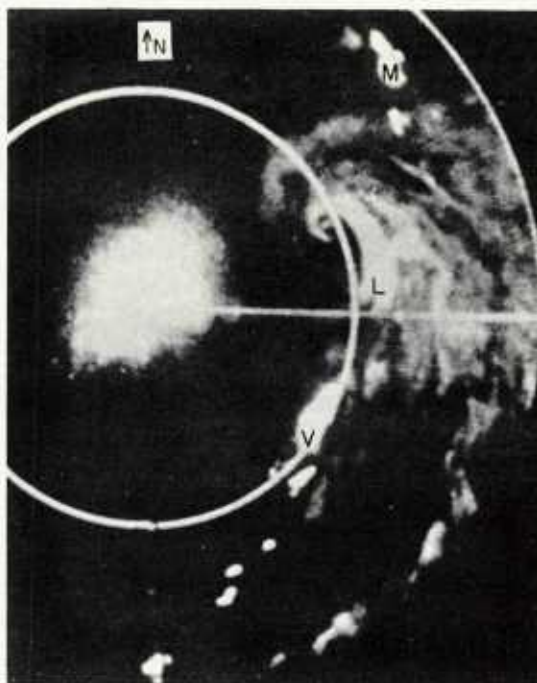


Figure 2.10. A Radar Presentation of Hurricane ABBY during the Formative Stage Taken at 1122 GMT, 10 July 1960 from the APS-20E Radar of a U.S. Navy C-121 (WV-3) Aircraft. The Range Circles Are at 50 Nautical Mile Intervals. The Bright Echoes Labelled V, L, and M Are Due, Respectively, to the Islands of St. Vincent, St. Lucia, and Martinique. (From [ 8].)

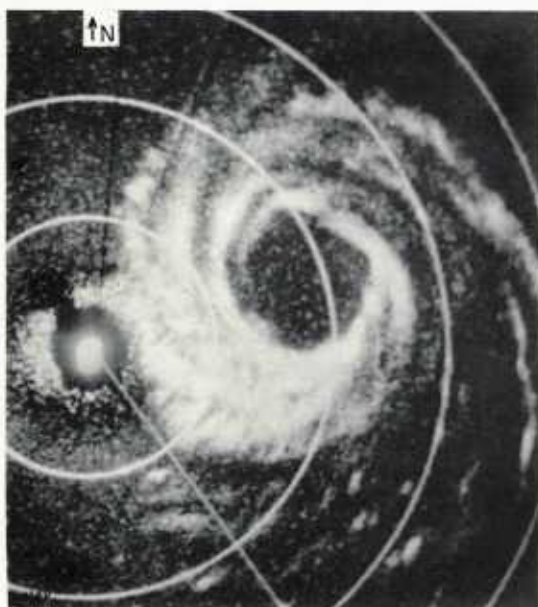


Figure 2.9. A Radar Presentation of Hurricane ALICE at about 2330 GMT, 1 January 1955 from the Air Search Radar of the USS MIDWAY. Range Circles Are at 20 Nautical Mile Intervals. At the Time of this Photograph the Hurricane Was about 300 Miles East of San Juan, Puerto Rico. (From [ 28].)

of operation in hurricanes in recent years. If all hurricanes provided such well-defined patterns and all reconnaissance aircraft were equipped with radar equipment having the capabilities of the APS-20E, the following discussion of the use of the wind and pressure fields in locating the center of tropical cyclones would hardly be necessary.

## 2.2.2 Pressure Center

The point of lowest pressure in a well-developed atmospheric disturbance is difficult to locate from aircraft pressure observations alone. The pressure center can be located by flying a pattern of the type shown in figure 2.14, in which the legs are shortened as the center is approached. The accuracy of the location of the center will depend upon the pressure gradients in the disturbance and on the accuracy of the pressure observations. In flying a pattern of this type the observer watches for the point of lowest pressure on each leg, as indicated by the dots on figure 2.14. After definitely establishing

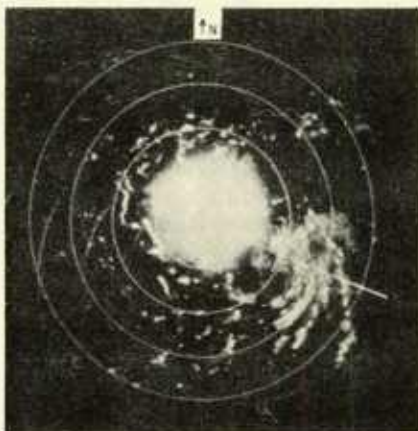


Figure 2.11. A Radar Presentation of Hurricane GRACIE Taken during the Deepening Stage at 0624 GMT, 23 September 1959 from the APS-20E Radar of a U. S. Navy C-121 (WV-3) Aircraft. The Range Circles Are at 50 Nautical Mile Intervals. The Storm Was Located about 325 Miles East-Southeast of Miami, Florida. Note the Curved Banda to the Southeast of the Aircraft and the Lack of a Definite Wall Cloud of the Type Shown in Figures 2.4 - 2.9. (From [ 31].)

that this point of lowest pressure has been passed and that the pressure is rising, the aircraft is turned sharply (in excess of 90 degrees) and the procedure is repeated. Locating the point of lowest pressure along each leg of the track is not as easy as it might first appear. It is often difficult to maintain the aircraft at the same height (or at the same pressure altitude) because of turbulence, and the readings made by the observer must be continually corrected for the fluctuations in the aircraft height.

From the pressure information gathered on the first leg, in figure 2.14, there is no way of determining whether the center is to the south or north of the track. If it were north of the track, the pressure would rise after the turn at A and a new plan would have to be laid out. In view of the strong wind speeds in the vicinity of tropical cyclones, the patterns would normally be flown with, rather than against the winds, and as a result the turns would always be toward the left (in the Northern Hemisphere) if the pattern is taking the aircraft nearer the pressure center. Difficulties can be encountered after the pattern has been established if the aircraft is turned through too large an angle. For example, a turn at point B along the dashed course would take the aircraft to the west of the center. After making the turn to the left at



Figure 2.12. A Radar Presentation of Hurricane HELENE Taken During the Deepening State at about 1700 GMT, 25 September 1958 from the APS-20E Radar of a U. S. Navy C-121 (WV-3) Aircraft. The Storm Center at the Time of this Photograph Was about 350 Miles East of Daytona Beach, Florida. (Official Photograph, U. S. Navy.)

point C' the pressure would begin to rise, rather than fall, and the observer would realize that the center had been missed.

A flight procedure of the type described above assumes that the isobars are circular, or nearly so, and this is a good assumption near the center of well-developed tropical cyclones [24]. However, disturbances just passing out of the wave stage may have marked asymmetries in the pressure field, and even multiple centers. For such cases a flight procedure of this type might not be a very efficient way of locating the point of lowest pressure.

The pressure center of a storm can usually be located quite closely by an experienced reconnaissance observer, using the technique described above, but often a considerable period of time is required in making the "fix". Fortunately, this technique can be abbreviated in most cases since other observations will be available for indicating the approximate location of the center. Fairly crude radar pictures, even poorer than presented in figures 2.11 and 2.12, would provide

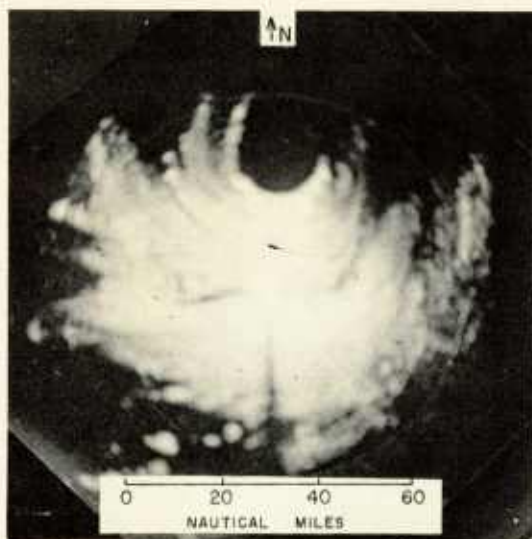


Figure 2.13. A Radar Presentation of Hurricane ESTHER Taken at 2018 GMT, 16 September 1961 from the APS-45 of a U.S. Navy C-121 (WV-3) Aircraft. The Return on this Radar, which Operates on a Wavelength of 3.2 cm., is Influenced to a Marked Extent by Attenuation in the Regions of Heavy Precipitation. As a Result Only a Portion of the Wall Cloud and the Inner Bands Are Shown. At the Same Time as this Photograph the 10-cm. APS-20E Radar on the Same Aircraft Showed the Wall to be Encircling the Eye and Bands Were Shown Over a Large Area in the Vicinity of the Storm Center. (Official Photograph, (U.S. Navy.)

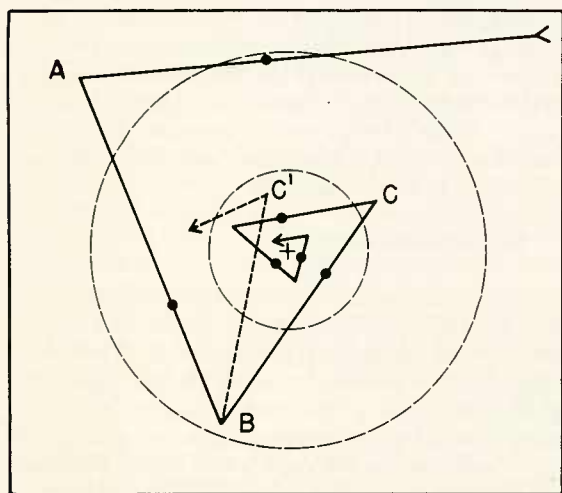


Figure 2.14. A Schematic Flight Pattern of the Type Used for Locating the Pressure Center of an Atmospheric Disturbance. The Isobars (or Contours of an Isobaric Surface) Are Indicated by the Dashed Circles. The Dots Show the Approximate Point of Lowest Pressure on Each Leg.

some assistance, and any type of wind observations could be used in locating the general area of the center of a tropical cyclone. A flight pattern of the type shown in figure 2.14, beginning in the outer portion of the storm, would be required only under rather unusual circumstances. A complete lack of definitive radar information might be encountered in the beginning stages of a tropical cyclone and, of course, the radar may be inoperative at times. Wind observations also may be completely lacking if the automatic wind-indicating equipment is malfunctioning and the sea surface is not visible from flight level.

The pressure center is often tracked during the developing phase of tropical cyclones, but the pressure gradient in such cases is quite weak and continuity is often poor. The organization of the convective cloudlines into a wall cloud, during the deepening stage, may not occur near the center of the previously tracked pressure center, with the result that quite large jumps in the center position may be indicated at the time the eye first appears [25]. It would seem likely that during the formative period, when the pressure gradient is weak over a fairly large area near the storm center, there may be several instances when short-lived convective systems result in well-defined, small-scale low pressure centers. During such periods a track of the point of lowest pressure, if this could be located from hour to hour, might jump around a great deal and be a very poor indicator of the motion of the disturbance as a whole.

### 2.2.3 Wind and Cloud Circulation Center

The problems of locating the wind center of tropical cyclones depend very much on the flight level of the aircraft and the method used for determining the wind velocity. On the penetrations of storms below the cloud bases (at altitudes ranging from 1,500 to 500 ft.) relatively little difficulty is usually encountered in locating the area of light winds near the storm center. Wind streaks on the ocean surface give the wind direction very closely, and the aircraft can be flown in such a manner as to keep the port wing into the wind. Difficulties may be encountered in extremely weak disturbances which are barely beyond the wave stage.

Wind direction becomes more difficult to assess from the state of the sea observations at wind speeds less than about 15 knots. This is especially true in the eye of a hurricane or typhoon where the sea is confused due to the swell.

As a result it is rather difficult to locate the exact wind center within the general area of light winds near the storm center. The wind center is usually easier to locate in tropical cyclones with small eyes than in those with large eyes.

Most aircraft penetrations of intense tropical cyclones are made at the 700-mb. and 500-mb. levels. The sea surface is seldom visible from these altitudes in the vicinity of the storm center; but, many of the reconnaissance aircraft are equipped with automatic navigation systems, using Doppler radar techniques, which provide essentially instantaneous flight-level winds. Therefore, the wind center of the storm can be found with relatively little trouble in well-developed storms, from the flight-level winds. Wind speeds at the 700-mb. and 500-mb. levels in such cases are nearly as strong as those near the earth's surface [14], and relatively strong winds often extend well inside the wall cloud at these levels. In most cases a definite wind center is probably easier to locate at these upper levels than near the surface.

Aircraft not equipped with Doppler systems can occasionally obtain drift or radar winds in the vicinity of land, but in most circumstances there would be no means of using the wind field to any appreciable extent in locating the storm center. However, the arrangement of the stratocumulus cloud deck within the eye into spiraling or concentric patterns, as illustrated by figures 2.2 and 2.3, is often such that an apparent cloud circulation center can be defined. This type of center is, therefore, used in place of a wind center in some cases. It would seem reasonable that the cloud circulation center defined from the stratocumulus clouds, which usually extend to about 6,000 or 8,000 feet within the eye, should correspond closely to the wind center defined from flight level winds obtained in the vicinity of the 700-mb. level. However, it is not known whether actual comparisons of this type have been made.

The position of the wind center at the surface can often be determined from the presentation on the aircraft radar. The character of the radar return from the sea is quite different in the area of strong winds than that obtained in the light wind area within the eye. The center of the so-called "hole in the sea clutter" which appears on the radarscope (fig. 2.1) is often used as the wind center of the storm [37]. The hole in the sea clutter is ordinarily smaller than the visual extent of the eye and is often displaced

somewhat from the geometrical center of the eye. Radar observations of this type cannot be made when the aircraft is in or very near the eye since the spurious ground return, which is always present in the vicinity of the aircraft, tends to obscure the differences which lead to the hole in the sea clutter [37].

## 2.3 Utilization of Surface Reports

### 2.3.1 Ship Reports

Surface synoptic reports from ships, when available, provide some assistance in positioning the center of tropical cyclones. However, in order to locate the center with an accuracy of the order of 25 to 50 miles the observations must be taken within 100 miles or so of the storm center. Reports taken at greater distances may be important for storm detection purposes and in some instances for detecting large changes in the storm track. The following discussion will be concerned with the utilization of reports taken within 75 to 100 miles of the center for the routine tracking of the storm center. This distance figure is arbitrary since it is difficult to specify the maximum distance from which the center can be estimated from surface reports. In the smallest hurricanes and in developing storms, reports made at 100 miles from the center would be of very limited assistance in locating the center position. On the other hand, in large well-developed hurricanes the symmetry may be great enough so that several reports at 200 miles from the center, in different quadrants of the storm, would provide sufficient information so that the center position could be estimated fairly accurately.

#### (a) Wind Direction

The wind direction is usually the most valuable information in locating the center of a tropical cyclone, from surface reports. The wind speeds would ordinarily be 30 knots or greater within 100 miles of the center and the wind direction would be relatively stable. By assuming that the air has an average inflow angle, relative to concentric circles drawn about the storm center, of  $20^\circ$  to  $25^\circ$  [30], a single report provides enough information so that a line can be drawn along which the storm center should be found. As illustrated by figure 2.15, the center might be found at any point to the left of A and along the line through  $X_1$  and  $X_2$ . Using the same technique for a second report at point B, the storm center would be located at  $X_1$ . Additional reports, if available, should also be used in the

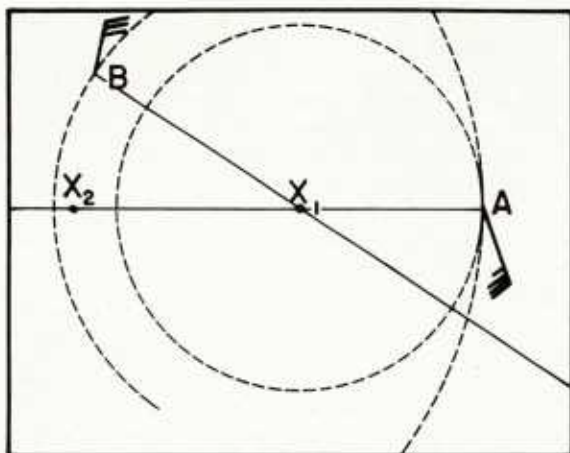


Figure 2.15. An Illustration of the Use of Surface Wind Reports for Estimating the Center Position of a Tropical Cyclone.

same way. In most cases where several reports are available, the lines would not tend to intersect at a point and the forecaster would have the problem of deciding which of the reports should be given the greatest weight. Difficulties of this type arise because of asymmetries in the storm, caused by variations in the inflow angle and errors in the reported ship positions. In rapidly moving storms the inflow angle in the sector to the right of the direction of motion should, in the mean, be considerably less than the assumed 20° to 25° value and the inflow angle to the left should be greater. Adjustments of this type may be helpful in some cases, but in most instances the subjective judgement of the forecaster will probably be the important factor in resolving these difficulties. Other types of information will be available in most cases to offer some guidance in the use of the surface reports.

#### (b) Wind Speed and Sea Level Pressure

Sea level pressure and wind speed observations taken near the storm center may be helpful in locating the center position if some recent information is available in regard to the minimum sea level pressure, the size of the eye, and the strength of the maximum winds. Near the eye pressure gradients are often very large (in excess of three millibars per mile in extreme cases [9]), but observations made at distances of 50 miles outside the eye may show deviations of only a few millibars from pressures reported in the storm periphery. In some cases 40 knot winds may be observed 200 miles from the center of a storm with maximum winds of 100 knots. In other cases, with maximum speeds

of 100 knots, 40 knot winds may be found within 50 miles from the center in some sectors of the storm. Therefore, in order to make use of reported speeds and sea level pressures some model of the storm, including an estimate of the size of the eye and the extent of hurricane-force and gale-force winds in the various sectors, must be employed. There is also the difficulty that some of the observations may have been taken within convective cloud bands, of the type shown to the north of the storm center in figure 2.8, where wind speed and weather conditions may be unrepresentative of conditions at this distance from the storm center. In fact, there may be a relatively high frequency of unrepresentative reports since the extreme conditions encountered in such areas may prompt the transmission of special observations.

#### (c) Other Elements

For purposes of locating the storm center the assistance provided by other reported elements, including the temperature, weather conditions, wave heights, direction of swell, etc., over and above that given by the wind velocity and pressure is very small. These elements can, of course, be very important in helping to assess the size and intensity of the storm and, to a limited extent, the direction and speed of motion.

A great deal of subjectivity is normally required in the use of ship reports for locating the center of tropical cyclones. The accuracy of the ship position is always in doubt since in many cases the bad weather associated with the storm has prevented celestial checks for many hours. The accuracy of radiopositions in specific areas as well as the capabilities of the individual vessels for determining positions of this type are seldom known.

#### 2.3.2 Land Reports

The problems of using surface synoptic observations from island and coastal stations in tracking tropical cyclones are very similar to those discussed above and essentially the same procedures should be followed. There is the advantage that the position of the station is accurately known but there is the disadvantage that local effects may result in unrepresentative values of some of the elements. In particular, wind direction and speed are often quite unrepresentative from stations on mountainous islands. Pressure may also be unrepresentative due to the effect of strong winds blowing over topograph-

ic features. The general rules which have been developed for evaluating local effects in surface observations at tropical locations [29 and 30] should be used in considering the island data.

Upper wind or temperature soundings are seldom of much assistance in positioning tropical cyclones, except that a more representative wind direction may be obtained at mountainous island stations by using the upper winds in preference to the surface winds. Upper wind and temperature data are often important as an indicator of storm intensity and in the utilization of certain prediction techniques for storm motion.

## 2.4 Utilization of Radar Reports from Land Stations

### 2.4.1 Radar Network

An extensive network of long-range weather radar stations now exists for the detection of tropical cyclones along the east and gulf coasts of the United States and along portions of the coasts of Japan and India. Similar radar equipment is also found at several island stations in tropical regions throughout the world. The problems of using radar information from coastal and island stations in locating and tracking tropical cyclones are somewhat different than those involved in using the airborne radar on the reconnaissance aircraft. This is primarily because, at the land stations, there is usually a long period of time between the detection of the outer portions of the storm and the appearance of the eye on the scope. During this period considerable effort is made to utilize the available information from the outer portion of the storm in approximating the center position. The utilization of the data from the storm periphery is not nearly so important in the case of the airborne radar since by flying toward the storm for a short period of time or, in some cases, by climbing a few thousand feet the eye can usually be detected by the radar.

The fact that the aircraft speed is much greater than the speed of motion of the storm is, of course, of very great advantage in the initial location of the storm center by radar. However, the radar observations made from the moving aircraft have a number of drawbacks for other purposes. Even if the exact location and speed of the aircraft were known at all times, it would be difficult to use the airborne radar presentation for computing the rate of motion of the storm center over short periods of time

or in computing the velocity of individual radar echoes within the storm circulation. As discussed below, computations of this type play an important role in locating and tracking hurricanes from land-based radars.

### (a) Radar Types

The primary weather radar network in the United States is equipped with the U. S. Weather Bureau WSR-57<sup>1</sup> set. This radar has a moderately high power output (peak power 500 kilowatts), a moderately narrow conical beam (2°), and operates at a wavelength (10 cm.) where precipitation attenuation is quite weak. Except for the peak power, this set compares favorably with the airborne set discussed in section 2.2.1 (the APS-20E) and the presentation of hurricanes, as illustrated by figure 2.16, is comparable with those shown in figures 2.4 - 2.8. The CPS-9 is in use at many military stations but the precipitation attenuation encountered with this 3-centimeter set, as illustrated by figure 2.17, limits its usefulness rather severely for long-range tracking of tropical cyclones. The FPS-68 and FPS-81, which are now being installed as replacements for the CPS-9 at some locations, operate at a wavelength of 5.6 centimeters and should be a great improvement for purposes of tracking tropical cyclones.

<sup>1</sup> The military nomenclature for this set is FPS-41.

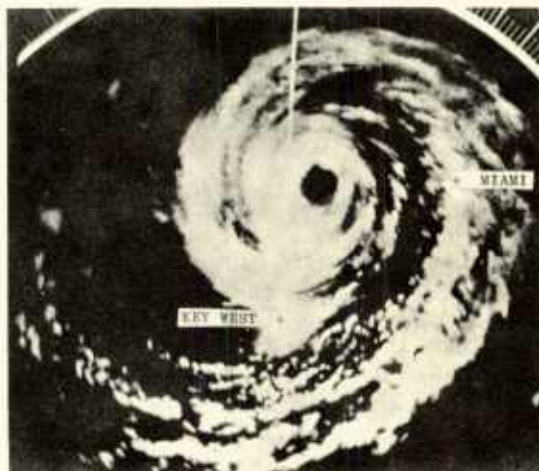


Figure 2.16. A Radar Presentation of Hurricane DONNA at 1340 GMT, 10 September 1960 from the U. S. Weather Bureau WSR-57 at Key West, Florida. The Distance from Key West to Miami Is Approximately 115 Miles. (From [7].)

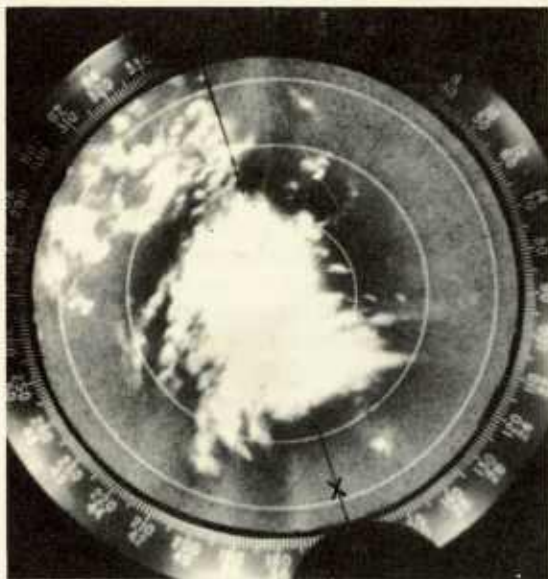


Figure 2.17. A Radar Presentation of Hurricane DONNA at 1012 GMT, 11 September 1960 from the U.S. Navy CPS-9 at Jacksonville, Florida. The Range Circles Are at 25 Statute Mile Intervals. The Storm Center Was about 70 Statute Miles from the Station at an Azimuth of 160° as Indicated by 'x'. Note the Marked Attenuation which Resulted in a Complete Lack of Return from the West Side of the Storm Center.

#### (b) Effective Range

The curvature of the earth is an important factor in limiting the range detectability of tropical cyclones. By making assumptions concerning the extent of the refraction of the radar beam, computations can be made of the minimum height to which the precipitation cells would have to extend at various ranges in order to be detected by radar. A curve based on computations of this type, with the assumption of standard refraction [38], is shown in figure 2.18. It can be seen from this curve that the precipitation cells in the tropical cyclone would have to extend above 40,000 feet in order to be detected from a station near sea level at a range of 250 miles. At 150 miles, however, the radar could illuminate the portion of the cells above 15,000 feet. There are hydrometeors above 40,000 feet capable of giving rather strong radar returns in the most intense tropical cyclones and in some cases these storms have been detected by land stations at distances greater than 200 miles. The earth curvature effect is, of course, much less important for the airborne radar. The radar horizon for an aircraft at

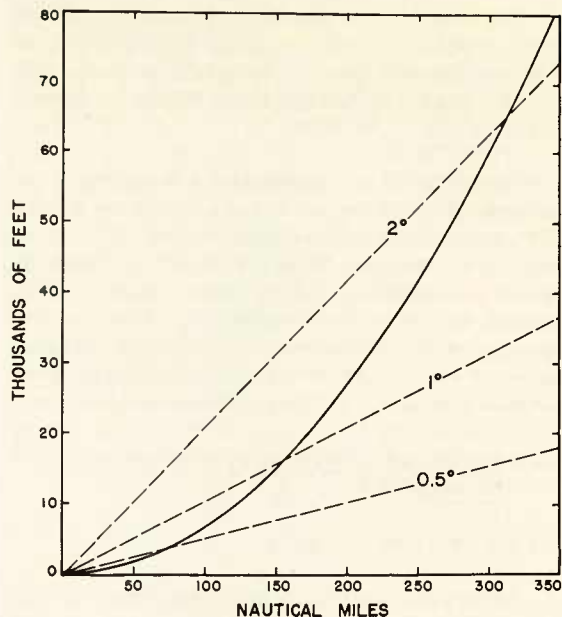


Figure 2.18. The Solid Curve Line Shows, as a Function of Range, the Minimum Height Above Sea Level at which a Radar Target Could Be Detected Due to the Curvature of Earth, under the Assumption of Standard Refraction of the Radar Beam. The Dashed Lines Show, as a Function of Range, the Linear Extent of Radar Beams of Several Angular Widths. The Angular Widths of the Beams of the APS-20E, WSR-57, and CPS-9 in the Vertical Direction Are 6.0°, 2.0°, and 1.0°, respectively. (From [18].)

7,000 feet would be about 100 miles away (fig. 2.18), so that from this altitude the airborne radar could see as much of the precipitation pattern at the 250-mile range as a surface radar could see at the 150-mile range.

#### (c) Beam Width vs. Range

The thickness of the radar beam as a function of range is also shown in figure 2.18. For the 2° beam of the WSR-57, defined by the angular distance between half-power points [3], the radar energy is covering a layer about 30,000 feet deep at 150 miles and more than 50,000 feet at 250 miles. The beam of the CPS-9 is about half of that of the WSR-57, while the new 5.6 centimeter sets mentioned above have conical beams with widths of about 1.5°. It can be seen from this figure that the return displayed on any of the weather radars results from the integrated effect of hydrometeors through rather deep layers. At great ranges, however, a large portion

of the lower atmosphere is offering no contribution because of the curvature of the earth. In cases when the storm center is at relatively close range the radar return would be from a layer which is much thinner and located much closer to the earth's surface. Some of the differences which are noted in the radar features of tropical cyclones, as viewed from different stations, undoubtedly arise from this difference. However, the portion of the storm illuminated by the radar beam, which depends upon the distance from the radar to the storm center, is not as important in the case of the tropical cyclone as it is with other atmospheric disturbances. This is because, as discussed earlier, the center of the storm is at about the same location at all heights; i.e., there is practically no tilt of the system with height.

#### (d) Vertical Scanning

In the previous discussion it has been assumed that the radar is being operated in the normal search mode with the beam horizontal or inclined upward by a degree or so. On both the WSR-57 and the CPS-9 the beam can be scanned in the vertical direction to give a range-height presentation. These presentations are helpful in some instances in interpreting the patterns seen on the plan-position-indicator (PPI) scope, but they would seldom provide any assistance in locating the storm center any more definitely or precisely than could be obtained from the PPI presentation. Possible exceptions are during the weakening or transforming stages when the storm center may have an appreciable tilt with height. In some instances the antenna axis may be elevated somewhat above the horizontal while scanning in the azimuthal direction. The altitude of the base of the layers viewed could, therefore, be very much greater than indicated by the solid curve in figure 2.18.

### 2.4.2 Characteristics of Tropical Storms as Seen by Radar

#### (a) Prehurricane Squall Lines

The first features of the approaching tropical cyclone detected by radar are lines of convective activity which appear to have no definite relationship to the wind field of the storm. Lines of this type, which have been called prehurricane squall lines by Senn and Hiser [34], are to be identified with patterns of the type shown 100 to 150 miles west of the storm center in figure 2.5 and to the north of the aircraft position in figure 2.8. The vertical extent of bands or lines of this

type is ordinarily less than that of the intense cells near the storm center, and it is unlikely that they could be detected by surface radar with any regularity at ranges greater than about 175 to 200 miles. Since these lines are not closely related to the wind field of the storm and do not move in any consistent fashion, they are of little, if any, value in approximating the center position. These somewhat isolated systems are not always present in the storm periphery and care must be exercised in distinguishing these from the first lines which are part of the basic spiral structure of the storm.

#### (b) Spiral Bands

The lines and bands within the main portion of the tropical cyclone tend to become arranged in much smoother patterns than most of the prehurricane squall lines and tend to parallel the wind direction. The individual cells within the lines move along the line in a much more definite fashion than those in the outer bands. Therefore, by tracing cell motion the experienced observer can make a fairly accurate distinction between the outer lines and those more intimately associated with the storm circulation. The velocity of the cells increases toward the storm center and the echo speeds near the center can be used as approximations to the wind speed [19 and 26]. Some of the spiral bands are composed of rather distinct convective echoes, as shown to the west and south of the storm center in figure 2.7 or to the north of the storm center in figure 2.8. In other cases the spiral structure is superimposed upon a rather uniform radar return, which is often referred to as the rain shield. This type of pattern is shown to the west of the storm center in figure 2.4.

The general pattern of movement of the spiral bands relative to the storm has not been definitely established. However, in some cases [33] the complete line propagates outward from the storm (at the same time as the individual cells move inward along the line toward the storm center). This was true for the long band to the east, southeast, and south of the storm center in figure 2.6. The duration of the spiral band is typically measured in hours while the cell duration is usually much less than 1 hour.

#### (c) "False Eyes"

There are irregularities in the radar echo patterns which might be erroneously interpreted as the eye by inexperienced observers. However, by tracking individual echoes these "false

eyes'' [36] can be easily detected since the echoes will be moving in about the same direction on opposite sides of the apparent eye. Echo motion is extremely difficult to trace from the airborne radar presentation because of the motion of the aircraft but "false eyes" can be identified by flying into these areas. These irregularities in the precipitation distribution are not associated with closed circulations in the wind field or with a pressure minimum.

#### 2.4.3 Spiral Overlays

As suggested by the previous discussion, the center of a tropical cyclone can be rather definitely established by tracing the motion of individual echoes about the eye. However, in many cases where the spiral bands are clearly indicated the eye will not be shown on the radarscope. The maximum range of the radar, the curvature of the earth, and attenuation of the radar signal by the heavy precipitation within the storm are all factors which prevent the eye from being detected by the radar in individual cases. Senn and Hiser [34] studied radar patterns in a large number of hurricanes and found that the curvature of the spiral bands could be used for inferring the location of the storm center, as illustrated by figure 2.19. They experimented with logarithmic spirals with incurvatures of  $10^\circ$ ,  $15^\circ$ , and  $20^\circ$  and found that in most of the patterns the center location could be most accurately approximated with the use of a  $15^\circ$  spiral overlay. They suggested that in some cases, especially at very low latitudes and relatively high latitudes, the  $10^\circ$  and  $20^\circ$  overlays might consistently give better results. They did not, however, provide rules for selecting which of the overlays should be used in individual cases. The overlays have been widely used in recent years, and it would appear from the data listed in the operational weather radar reports that the  $15^\circ$  overlay is used in nearly all cases.

In an analysis of 443 bands in five hurricanes, Senn and Hiser [34] found that by using both the  $15^\circ$  and  $20^\circ$  spiral overlays the storm center could be estimated within 15 miles in 83 percent of the cases. Errors were usually small when the band extended through an arc in excess of  $180^\circ$  (relative to the storm center), and overlay determination of the center position was almost impossible if the band extended through an arc of less than  $90^\circ$ . They indicated that errors were much smaller when the mean radius of curvature of the bands was less than 50 miles. In the operational use of the spiral overlays the observer can hardly experiment in the use of more than one overlay, unless he is trying to



Figure 2.19. An Illustration of the Spiral Overlay Technique in Locating the Center of a Hurricane. (From [34].)

verify the center position provided by other means. Also, in most cases where the mean radius of curvature of the bands is less than 50 miles and the bands extend through at least  $180^\circ$  the eye would be shown on the radarscope, and there would be no need to use the overlay.

In order to obtain some idea of the conditions under which the overlays have been used and the accuracy attained by this technique, a comparison was made of the spiral overlay center positions reported in the operational weather radar reports and the "actual" storm positions as determined from the official U.S. Weather Bureau storm track. Radar data were taken from the teletype circuits for all available hurricanes of 1959, 1960, and 1961. The results of this study, based on 59 reports in four hurricanes, suggest that the spiral overlays were often used when the storm center was more than 100 miles from the station and rarely used if the center was within 50 miles of the station. No information was available on the distance of the bands from the hurricane center or on the arcs subtended by the bands. The reported spiral overlay center positions were all within 55 miles of the "actual" position and nearly 60 percent of the positions showed differences of less than 25 miles. These

differences are somewhat larger<sup>1</sup> than the values given by Senn and Hiser. However, some of this difference may be accounted for by the fact that the "actual" positions taken from the storm track are subject to some error. Even the lower accuracy, as obtained from the operational reports, is comparable with that attainable in many cases from the reconnaissance aircraft, as discussed later in section 3.2.

<sup>1</sup> For more detail see the "Proceedings of the Tenth Weather Radar Conference," April 22-25, 1963, pp. 202-207.

It is surprising that a few of the spiral overlay positions did not show very large errors of the type which might have resulted from the use of the overlay on some of the prehurricane squall lines. However, since most of the reports were from United States coastal stations and the storm position was fairly accurately known, it was probably quite easy to recognize when the spiral overlay positions were definitely erroneous. Much larger errors might be obtained in some cases if a large sample of spiral overlay positions were read from shipboard radars

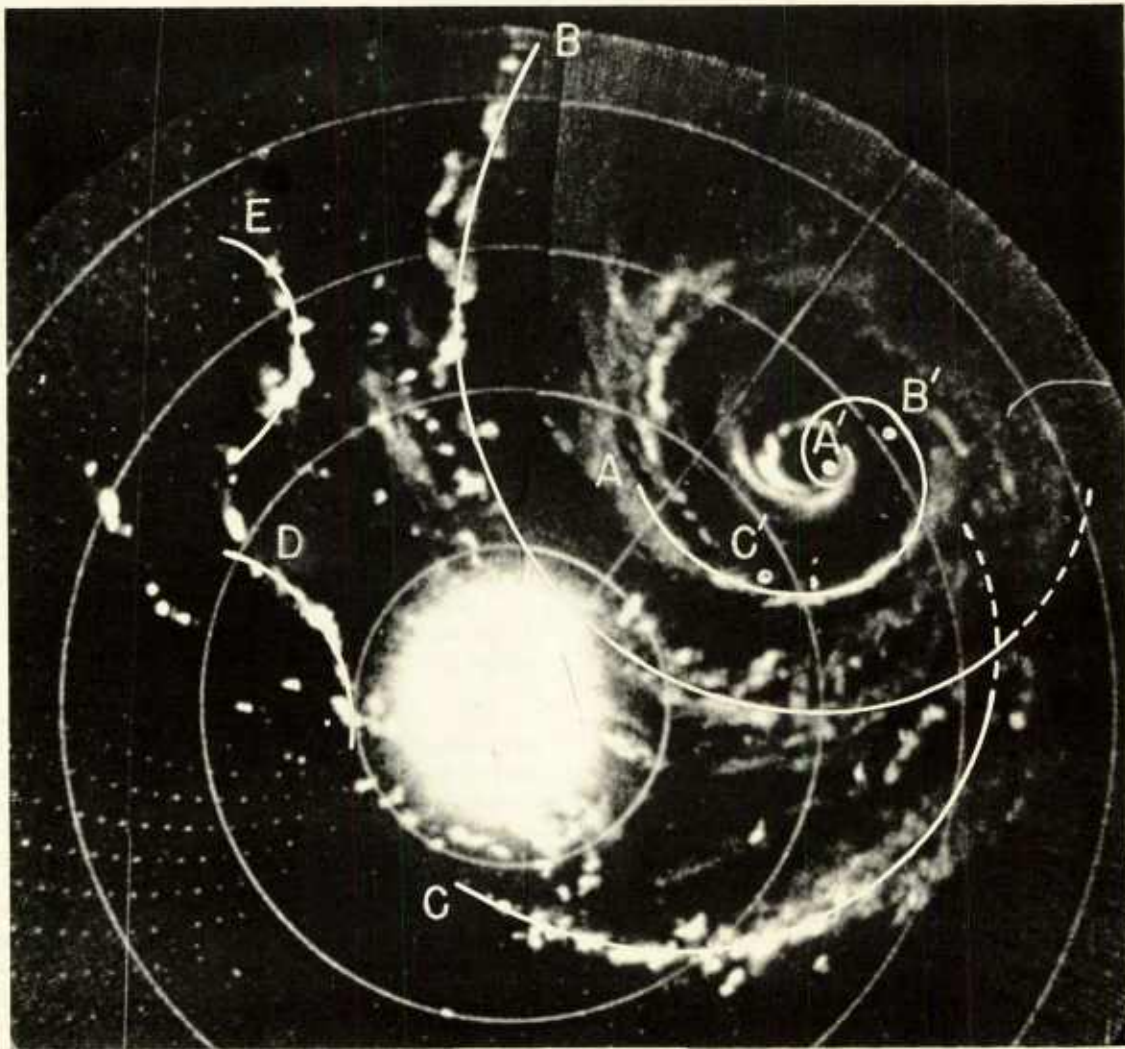


Figure 2.20. The Radar Presentation of Hurricane ESTHER Shown in figure 2.5 with Superimposed Portions of the Senn-Hiser 15° Spiral Overlay. The Dots A', B', and C' Indicate the Center Positions Which Would Have Been Obtained by Using the Radar Lines Beginning at A, B, and C.

while the storms were far from land.

Some of the difficulties in using the spiral overlays are illustrated by figure 2.20, on which portions of the 15° overlay have been entered on several of the lines. The curvature of the group of cells in lines marked D and E would give completely misleading information regarding the location of the storm center. These patterns hardly qualify as lines and the total extent is rather small compared to most of those considered by Senn and Hiser [34]. The lines marked A, B, and C are much more extensive as far as length and arc subtended. Use of the spiral overlay on the A line, which was closest to the center, would have given a fairly accurate location of the storm as indicated at A'. The errors in center position obtained in using the overlay on B and C (at B' and C') would have been about 30 and 45 miles, respectively. For most purposes estimates with this degree of precision would be useful, especially if made when the storm is in an area where other information is scarce. The selection of bands or lines to be used with the spiral overlays would appear to be rather difficult, and no rules can be stated other than the rather general considerations mentioned previously. Perhaps it will be possible to set down more definite rules for selecting bands to be used with the spiral overlays after several more years of experience in the use of this technique.

The possible applications of the spiral overlay technique by the aircraft reconnaissance observer are fairly obvious. The overlays can be used on the outer bands for an indication of the center position in planning the penetration track. In such cases the spiral overlay position would probably not be transmitted from the aircraft. The overlay position may be transmitted in other instances, especially on night missions when penetrations of the storm core are seldom made. However, on many of the night tracking missions the aircraft can get sufficiently close to the storm center to definitely identify the eye on radar without encountering difficult flight conditions.

The accuracy of "fixes" from land and airborne radars is considered in a later section. This is, of course, a much more important problem in the case of the airborne radar, especially if the storm is far enough out to sea so that no land returns appear on the radarscope. All ranges and bearings in these cases must be measured relative to the aircraft, and any errors in the aircraft position will influence the accuracy of the reported geographical position of the

storm center.

## 2.5 Utilization of Satellite Information

### 2.5.1 Cloud Photographs

The impact of weather information from satellites on the problems of hurricane detection and tracking is clearly demonstrated by Dunn and staff [10] who present satellite photographs of no less than five hurricanes in their discussion of the 1961 hurricane season. Photographs of four of these storms are reproduced in figures 2.21 - 2.23. According to their discussion TIROS III gave the first evidence of the formation of hurricanes ANNA and ESTHER and offered valuable assistance in tracking hurricane DEBBIE, when the storm was in the eastern Atlantic beyond the reach of aircraft reconnaissance from Puerto Rico or Bermuda.

Many descriptive studies of atmospheric disturbances utilizing satellite photographs have been published in recent months, but there has been very little consideration of the accuracy of positioning of individual cloud systems. The stability of the satellites to date has not been adequate for precise positioning, except in cases where clearly identifiable surface features are shown. The nephanalyses prepared from the satellite transmission for the facsimile circuits, as shown on figure 2.23, usually indicate an accuracy of  $\pm 2^\circ$  of latitude in the positioning of systems drawn on these charts. By working directly with the satellite photographs greater precision might be expected. There is little doubt that with improvements in stabilization, in camera techniques, and in data reduction methods, the geographical positioning will be better with data from future satellites.

The accuracy of hurricane positions, as obtained from the satellite transmissions, depends upon the precision with which the hurricane center can be identified from the photographs of the cloud distribution as well as on the geographical positioning of the selected center position. The problem of identifying the exact center of the tropical cyclone is one in which only limited improvement should be expected. It can be seen from figures 2.21 - 2.23 that clearly defined center positions are not given, and there is no reason to expect that the hurricane eye will be in the exact center of the cloud masses which may extend over regions several hundreds of miles in diameter. In cases where definite spiral patterns can be detected in the cloud masses, it may be possible to use some type of overlay to assist in locating the storm center as is done with the



Figure 2.21. Hurricane ANNA as Observed by TIROS III at 1548 GMT, 21 July 1961. Most of the Coastline of Colombia Can Be Seen Southwest of the Cloud Mass. The East-West Extent of the Cloud Mass Is in Excess of 300 Milcs. (From [ 10].)

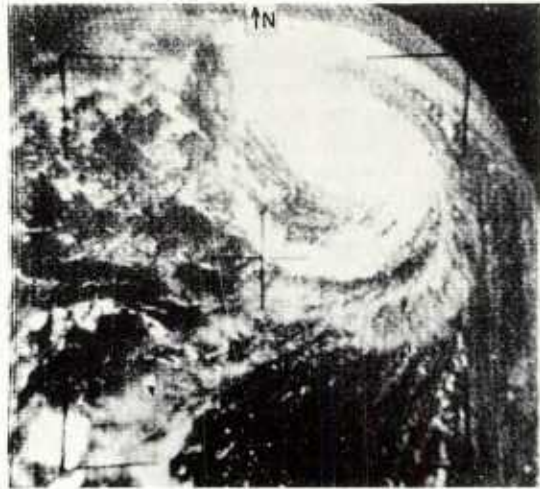


Figure 2.22. Hurricane BETSY ss Observed by TIROS III at 2015 GMT, 8 September 1961. The Center Was About 900 Miles East of Norfolk, Virginia. (From [ 10].)

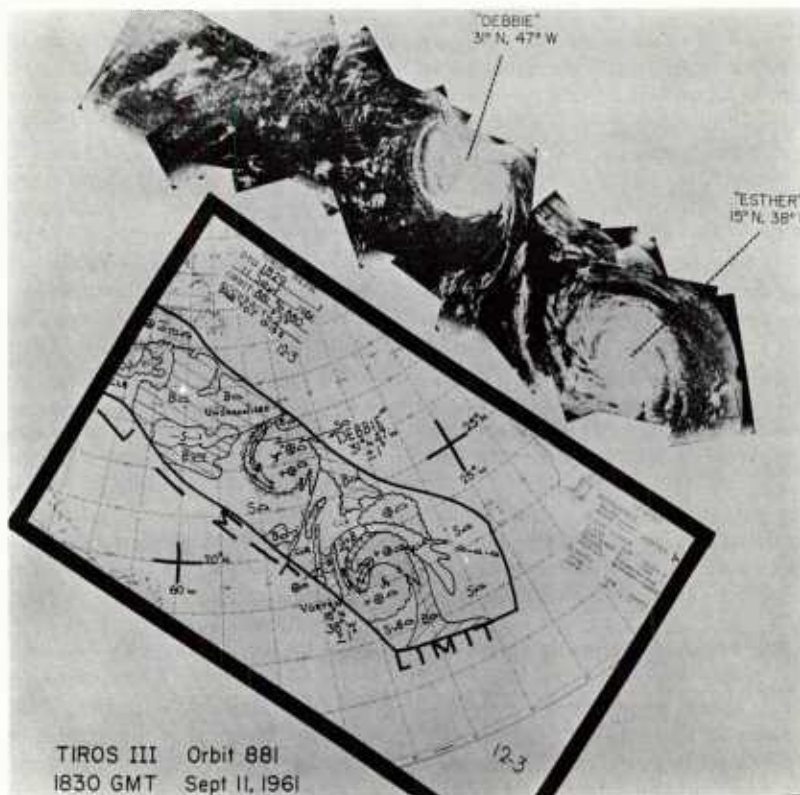


Figure 2.23. Cloud Mosaic of Hurricane DEBBIE and ESTHER and Operational Nephanalysis Msde from the Picture. The East-West Extent of the Cloud Masses Associated with each Hurricane Exceeded 500 Miles. (From [ 16].)

radar bands.

The ultimate which can be expected in delineating the storm center can perhaps be judged by an actual photograph of hurricane DEBBIE taken from the Mercury spacecraft while over the Atlantic on 13 September 1961 (fig. 2.24). This photograph shows a definite center but the precision with which the center of the area of reduced cloudiness can be identified is probably much poorer than locations given by radar or by aircraft penetration. In many cases the eye of the storm will be completely covered with cirrus or even middle level clouds [17]. This may have been the case at the times of figures 2.21 - 2.23, or perhaps the viewing angle was such that the

reduced region of convective cloudiness at the storm could not be detected.

#### 2.5.2 Infrared Measurements

The infrared radiation measurements, which are provided by the satellite, may be useful in locating the storm center in some cases but the potential does not appear great. The field of view of the IR (infrared) detector has been of the order of 60 miles but some reduction may be possible in future satellites. Perhaps the storm center could be detected in the IR return if the field of view were reduced slightly and the satellite passed directly over the storm. If the eye is relatively free of upper cloud, then the warm



Figure 2.24. Hurricane DEBBIE as Photographed from the Mercury Spacecraft Orbiting the Earth at 1416 GMT, 13 September 1961. (From [1].)

ocean surface or the tops of stratocumulus in the eye will show up as a hot spot. On the other hand, if the eye is completely overcast with cirrus the storm center would be expected to appear as a relatively cold area, since cloud heights near the storm core are probably somewhat higher than in the outer portion of the storm. At nadir angles<sup>1</sup> of 45° and greater there would be little chance of seeing the ocean surface and the relatively small contribution from the inside portion of the wall cloud at upper levels, which might be viewed, would not offer enough contrast for positive identification.

The above discussion would suggest that, at the present stage of development, the satellite information relating to center location of tropical cyclones is subject to quite large errors in comparison with those provided by other means. It is difficult to arrive at an estimate of the maximum errors which can be expected in tracking tropical cyclones from the satellite cloud distribution patterns. The operational nephanalyses indicate that positioning errors may be as great as 120 miles (2° of latitude), and the center selection from a large cloud mass of the type shown in figure 2.23 might conceivably add an additional error of as much as 100 miles. In view of the possibility of errors of this magnitude, the satellite can hardly be considered as a replacement for aircraft reconnaissance for purposes of tracking tropical cyclones. The greatest value of the satellite information in this problem in the foreseeable future would appear to be in the detection of storm areas and in the tracking of these systems in the large oceanic expanses which are nearly devoid of other types of weather data.

## 2.6 Floating Automatic Weather Stations

A network of free floating or anchored automatic weather stations could provide considerable assistance in tracking tropical cyclones in sparse data areas. The utility of systems of this type has been demonstrated by the NOMAD<sup>2</sup> (Navy Oceanographic Meteorological Automatic Device) station [35] which, in recent years, has been operated in the central Gulf of Mexico and which was credited with the detection of hurricane ETHEL of 1960 [8]. Wind and pressure reports from floating automatic stations at isolated positions would, of course, provide no more information than given by individual ship

reports. However, stations of this type could be placed in definite patterns within climatologically preferred regions of hurricane activity. A north-south line of anchored stations of this type to the east of the Lesser Antilles during the summer and autumn months would be extremely valuable for the detection and tracking of tropical cyclones. The precision with which the storm center could be positioned would depend upon the spacing of the stations within the line. Data from stations at 50 mile intervals could probably be used to indicate the center position with an accuracy of the order of 5 to 10 miles as the storm moved through the line, and a station spacing of 100 miles should allow positioning of the center to within 25 miles in nearly all cases. A series of north-south lines of stations might be arranged in order to give a number of fixes as a storm moved westward. An east-west separation of the order of 300 to 400 miles would give about one fix per day for a storm moving at the normal rate of speed in this region. Similarly, a line of automatic stations parallel to the shoreline of the Gulf of Mexico and just beyond the range of the coastal radars might prove quite valuable in detecting rapidly-developing tropical storms and in tracking storms during periods when aircraft reconnaissance observations are not available.

Floating stations with anchors of the type used on the NOMAD system [35] would probably be more practical than free floating stations. The free floating stations would require a network of coastal radio direction finding stations for accurate positioning. Also, there is the additional problem that in some oceanic regions positioning of this type would be subject to considerable error.

A program of the type discussed above would be expensive to establish and maintain but the stations might be used for other purposes outside the hurricane areas during the winter and spring months.

## 2.7 Microseisms

Microseisms generated by tropical cyclones have a distinct character and can be detected for distances as great as 500 to 1,000 miles from the stronger storms. In an attempt to make use of the microseisms in locating and tracking tropical cyclones, a network of tripartite microseismic stations was established by the U.S. Navy in the western Pacific and West Indies areas during the middle 1940's [12]. It was found that irregularities in the earth's crust, among other factors, prevented accurate positioning from the

<sup>1</sup> The angle between the point directly below the satellite and the point at which the satellite camera is directed.

<sup>2</sup> The non-Navy and more commonly used designation for NOMAD is MAMOS (Marine Automatic Meteorological Observing Stations).

microseismic observations. The U.S. Navy microseismic stations are no longer maintained but some geophysical observatories still make observations of this type in areas where tropical cyclones occur. These observations are currently used to a very limited extent, if at all, in the operational tracking of tropical cyclones. If this technique had been developed prior to the time of aircraft reconnaissance, it seems likely that it would have received more attention and would perhaps have been developed to a greater extent.

## 2.8 Hurricane Beacons

A number of suggestions have been made in regard to a hurricane beacon which would float in the eye of a tropical cyclone and be tracked by long-range radio direction finding equipment. Several schemes have been devised involving a balloon-borne radio transmitter which would be retained at some predetermined level by a ballast system [4 and 13]. An attempt has also been made to use a light weight ball (the so-called Brango Ball<sup>1</sup>) which would float on the ocean surface and be carried readily by the wind.

Some developmental work has been done on

<sup>1</sup> After Capt. Nicholas Brango, USN, who suggested this technique and who was instrumental in much of the development work done along this line.

some of the proposed beacon systems, but it has not been established that the wind field is such as to retain a balloon within the eye for extended periods or that the radio bearings from such a system would be accurate enough to satisfy operational needs. Even if a balloon remained in the eye it could hardly be expected that it would remain near the center. An uncertainty in position roughly equal to the radius of the eye would therefore be present in all fixes.

The wavelength used by a beacon should be sufficiently long to enable subhorizon reception and thereby permit tracking at distances very much greater than is possible from radar. Any system of this type would have the disadvantage that aircraft penetration of the storm core would be necessary to place the system within the eye.

None of the hurricane beacon systems can be considered operational at the present time. In view of the potential of weather satellites for tracking cyclones over remote oceanic regions, it would appear unlikely that any great effort will be made to develop an operational hurricane beacon. However, pressure-height, temperature, and moisture data could be telemetered from a beacon system and thus provide information on storm intensity. In contrast, there appears to be little chance of assessing storm intensity from the type of satellite information available at the present time.

### 3. OPERATIONAL ASPECTS OF HURRICANE TRACKING

#### 3.1 Charting the Storm Track

In charting the course of a tropical cyclone the forecaster will often have several of the types of data described above, and these data will often give conflicting indications as to the position and speed of motion of the storm. Decisions must continually be made as to which of the data should be given the most weight in defining the storm track. The forecaster must consider the problems facing the reconnaissance or radar observer in identifying the storm center, and these problems vary, of course, with storm position, intensity, and many other factors. These parameters have been discussed in some detail in the previous sections but the question of the accuracy of the geographical position selected as the storm center was deferred in the case of the reconnaissance and radar observations. Some very general comments were made in regard to the accuracy of center fixes determined from satellite and ship observations.

Some of the problems associated with the accuracy of the fixes will be discussed in the following sections but very little quantitative information can be presented. There is, of course, no means of establishing the actual track of the storm center on a current or postanalysis basis. About the best that can be done, in a discussion of the accuracy of the fixes, is to give some rough limits and some information on the relative accuracy of fixes obtained by various techniques and in various areas. The sources of error can also be examined only in a qualitative fashion.

As an introduction to the topics to be discussed in the following sections, we will consider

some of the tracking problems which might arise with a well-developed hurricane originating in the extreme eastern Atlantic and moving on a west-northwest course to the north of Puerto Rico and eventually approaching the Carolina coast (fig. 3.1). Most hurricanes form much further west, and it would only be in very rare instances that the hurricane forecaster would be faced with the problem of tracking a storm over the longitudinal extent shown in this figure.

##### 3.1.1 Eastern and Central Atlantic

###### (a) Land and Ship Observations

The eastern Atlantic region is beyond the range of Navy reconnaissance aircraft from Puerto Rico or the Air Force planes from Bermuda. Storms in this area must, therefore, be tracked by techniques quite different than those normally used in the western Atlantic. Observations from the Cape Verde Islands may at times give some indication of the presence and location of hurricanes but data of this type would be of very limited assistance in locating the storm center or in assessing changes in storm intensity even 12 hours after the center had passed the islands. Ship reports are quite numerous along certain shipping lanes in the eastern Atlantic and in some cases these observations, along with the island reports, would be quite helpful in detecting tropical cyclones. Only rarely, however, would the ships be caught close enough to the storm center so that an accurate fix could be obtained. Some of the techniques and problems of using surface synoptic reports have been discussed in a previous section.

After our hypothetical storm moves some distance off the African coast there are large

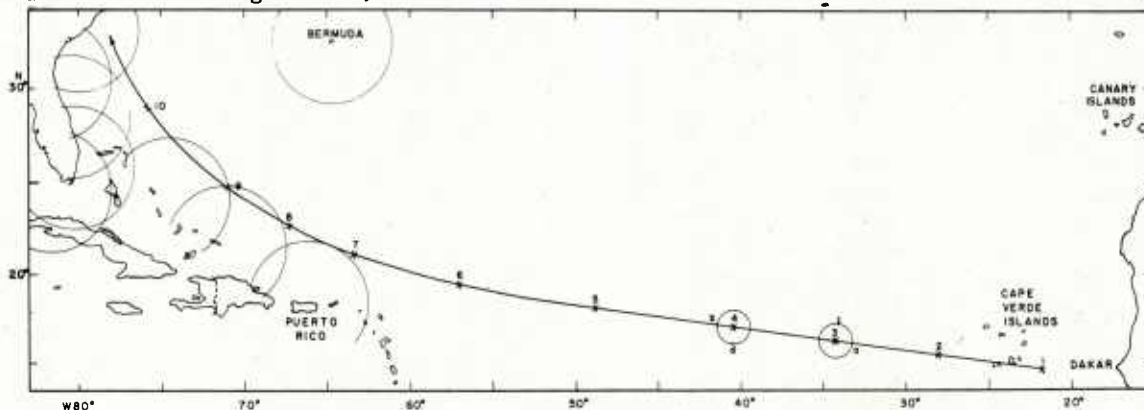


Figure 3.1. A Hypothetical Hurricane Track with Positions at 24-Hour Intervals Marked by x's. The Approximate Maximum Extent of Radar Coverage from Land Stations in the Western Atlantic Area Is Indicated by the Arcs Drawn about Individual Stations.

areas in which ship reports are quite sparse, and many of the available reports are not relayed on a routine basis for the use of the hurricane forecasters in the United States. Actually the number of ships in any given oceanic region is usually considerably greater than would be suggested by all the available synoptic observations. The nonreporting ships are, however, requested to send reports when conditions are encountered which might indicate the presence of a tropical cyclone. Therefore, in viewing the large tropical areas devoid of ship reports, the forecaster has some consolation in the fact that ships are probably within these areas and are not reporting bad weather. Of course, there are instances when extensive systems of bad weather are present within areas which are not being traversed by ships.

#### (b) Commercial Pilot Reports

Commercial aircraft flights on the routes between Europe and Brazil and between the Cape Verde Islands and Puerto Rico occasionally report areas of unusual cloudiness and weather conditions in the area of sparse surface coverage in the central Atlantic. Flight level wind data have not been available from these aircraft and the total information contained in the reports is seldom adequate to definitely establish the presence of a tropical cyclone. Some of the weather areas reported by this means develop into tropical cyclones but most of them do not. The flights in the central Atlantic area are not frequent enough so that pilot reports can be considered of much value in tracking existing storms.

#### (c) Satellite Pictures

The potential value of satellite observations is greatest in the sparse data areas such as the east and central Atlantic. As described previously, TIROS II detected hurricane DEBBIE in this area when the storm was west of the island stations but beyond the reach of reconnaissance aircraft. The satellite observations seldom show a definite center (figs. 2.21 - 2.23) and the positioning errors, as discussed previously, may be appreciable. The effect of an error of 60 miles<sup>1</sup> in the reported position on successive days is considered on our hypothetical storm track. Errors of this magnitude on days 3 and 4 could result in fixes at points a and b (fig. 3.1) and therefore indicate a speed of

motion of 20 knots when the actual speed is 15 knots. It is also apparent that errors in the indicated direction of motion of as much as 20° could result by using fixes at points c and d.

#### (d) Airplane Reconnaissance Reports

While hurricanes are in the eastern Atlantic, it is seldom that more than one fix per day will be available and these will ordinarily be subject to fairly large errors. As the storm moves into the area which can be covered by aircraft reconnaissance (roughly west of 45° W.) the accuracy of the fixes should improve but the frequency will probably not exceed two fixes per day until the storm is west of about 55° W. If more than one fix per flight is attempted there will be a time separation of only a few hours, and the errors in location will be such as to render the indicated direction and rate of displacement quite unreliable. For example, 15-mile errors in fixes made 6 hours apart will lead to errors of the same magnitude as those discussed above in connection with fixes on days 3 and 4 of our hypothetical storm (fig. 3.1). In areas where as many as two reconnaissance fixes per day are available, the satellite data are of very limited value in tracking tropical cyclones.

### 3.1.2 Western Atlantic, Caribbean, and the Gulf of Mexico

#### (a) Radar Reports, Land Based and Airborne

The frequency of fixes will often increase to four or more west of 55° W. and dozens of fixes will be available from radar as the storm approaches certain land areas. Even greater care must be exercised in computing the direction of motion between fixes over relatively short intervals, even though the errors in fixing the storm center position may be relatively small compared to those in other areas. Using 200 miles as the effective limit of the radar for tracking well-developed tropical cyclones, our hypothetical storm would barely be within range of the island or coastal radars until it approached the Carolina coast (fig. 3.1). Obviously, many mature tropical cyclones will pass off the east coast of the United States well beyond the range of the radars along the coast or at Bermuda.

The distribution of radar stations is such that they are of very little assistance in tracking hurricanes in the central and western Caribbean and in the southwestern Gulf of Mexico. Thus, in many areas accurate tracking of Atlantic hur-

<sup>1</sup> The operational nephelometer usually give a 2° of latitude for the accuracy of location. Difficulties in center selection introduce additional uncertainty.

ricanes is dependent upon the accuracy of the reconnaissance fixes determined either by penetration of the storm center or from the airborne radar. Because of the problems of center selection, the radar fixes from land stations should not always be considered more reliable than those obtained from the airborne radar. In some instances, however, the land-based radar fixes have proved more reliable than those obtained by the reconnaissance aircraft after penetrating the storm core.

### 3.1.3 Other Regions

In other geographical areas the problems are quite different than those outlined above for the Atlantic. Loran is probably poorer in most tropical regions than the western Atlantic, but in many areas islands are more uniformly distributed and radar fixes are possible over a large proportion of the total area. The number of land-based radars is greater in the western Atlantic than in any other tropical area, but considerable assistance in storm tracking can be expected in the western Pacific from radars at Okinawa and Japan and in the Bay of Bengal and the Arabian Sea from radars in India. The complete absence of aircraft reconnaissance in many areas changes the tracking problem considerably and often storm tracking reduces to the problem of making intelligent use of the available ship reports.

### 3.1.4 Plotting the Storm's Position

Center fixes are often plotted on navigation charts of a fairly large scale (of the order of 1:1,000,000) and it is possible to include considerable information in addition to the position and time. The type and accuracy of the fix and the size of the eye should be included whenever this information is given. Different symbols — dots, open circles, triangles, etc. — can be used to differentiate between the types of fixes, and circles of variable size can be drawn to show the estimated accuracy of the fixes. Circles in a different color can be used to indicate the eye diameter. Often a group of fixes taken over a period of an hour or two, which appears to be inconsistent, will all fall within the reported eye. Perhaps this is about the best that can be expected in many cases. Apparent erratic fixes may arise in some cases because of the combined use of the circulation, pressure, and radar centers.

The preparation of a storm track on a post-analysis basis is, of course, somewhat simpler than tracking the storm on an operational basis.

Additional reports are often available, and much of the reconnaissance and radar data will be available in a checked form for use in postanalysis. However, many of the same problems of judgment arise as in the operational tracking, and the official tracks of tropical cyclones are open to considerable doubt in many areas. We should again emphasize that, in order to prepare a tropical cyclone track on an operational or postanalysis basis, the forecaster must be thoroughly familiar with the various types of data available to him and must consider their relative merits and limitations at every step in his analysis.

## 3.2 Accuracy of Reconnaissance Fixes

In the postflight summary of each reconnaissance mission some information is usually given in regard to the type of navigational fixes and the estimated accuracy of the fixes. Data of this type for all Navy flights into hurricanes in the 1958-1961 period are shown in figure 3.2. The plotted data usually refer to several fixes and, in figure 3.2, have been plotted at the approximate mean position of the storm during the flight. In most cases these data refer to the aircraft positions rather than to the storm center positions and do not take into account the errors which may be introduced in selecting the storm center. The actual accuracy in storm positions would, therefore, be expected to be somewhat less than indicated by the data shown in this figure.

### 3.2.1 Celestial Navigation and Dead Reckoning

The fixes east of about 54° W. were based on celestial navigation or on dead reckoning and most of the reports indicate an accuracy of 20 to 30 miles. Greater accuracy is attainable from celestial navigation under favorable conditions but, of course, this technique can be used to a very limited extent within the hurricane circulation. Often a celestial fix is obtained just outside the hurricane and dead reckoning is used during the penetration.

### 3.2.2 Doppler Navigation

The aircraft of the U. S. Air Force reconnaissance unit at Bermuda and the National Hurricane Research Project have for several years been equipped with automatic navigation systems employing the Doppler radar principle. The Navy reconnaissance aircraft were partially equipped with systems of this type in 1962 and should be fully equipped in 1963. These navigation systems are probably capable of providing somewhat more accurate fixes in the area east of 55° W. than indicated in figure 3.2. The

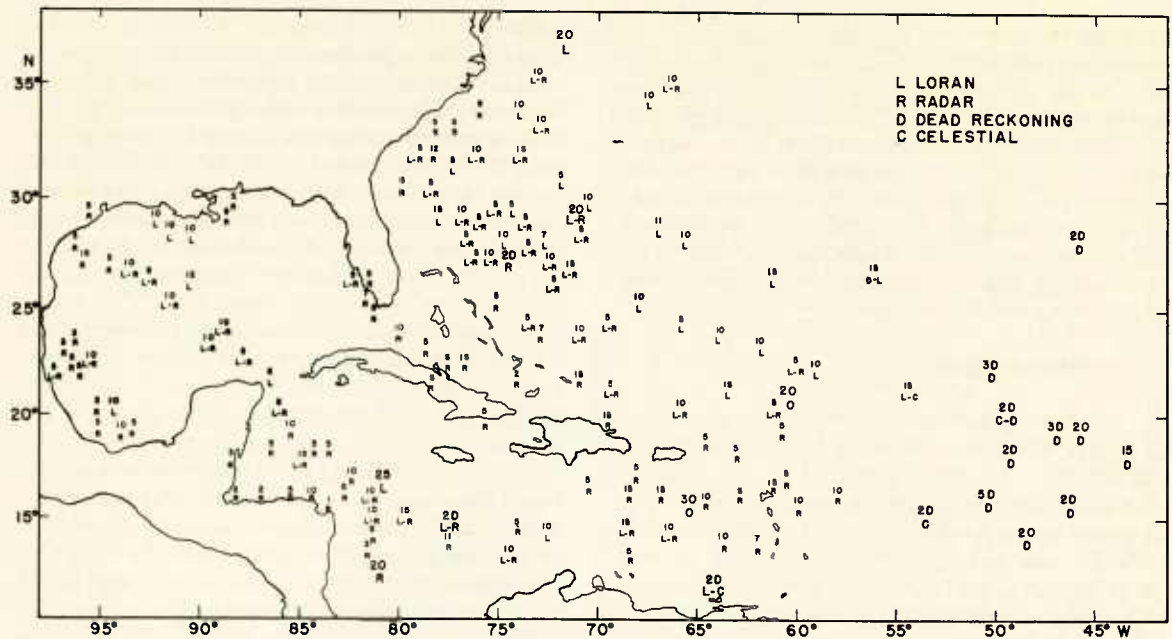


Figure 3.2. The Type and Accuracy of Navigational Fixes Reported by U.S. Navy Hurricane Reconnaissance Flights during the 1958-1961 Period. The Figures Give the Reported Accuracy in Miles and the Letters Indicate the Type of Fix According to the Key in the Upper Right. All Reports Indicating an Accuracy of 20 Miles or Poorer Are Shown by Larger-Sized Numbers and Letters. In Many Cases Two or More Techniques Were Listed and the First Two Have Been Shown, Except that Dead Reckoning Has Been Omitted if It Were Listed in the Second Position.

manufacturers of the automatic navigation systems usually claim an accuracy of 1 to 2 percent of the distance travelled. Rather detailed checks have been made by the National Hurricane Research Project which indicate that upon return from flights of about 10 hours, or about 2,400 miles in length, the errors are usually less than 25 miles. In a few cases larger errors were found, with a maximum error of about 65 miles. It is possible in most cases to check the error only upon return, and it may have been that during portions of the flight the position error exceeded that shown at the end of the flight. Compensating errors during the return portion of the flight would be expected if there are systematic errors due to the motion of the water. The Doppler system gives the ground speed relative to the water surface, and errors will be present if the surface "seen" by the radar is moving.

### 3.2.3 Loran and Radar Navigation

The data shown in figure 3.2 would suggest that loran coverage extends eastward to about 55° W. except south of 20° N. The loran accuracy in the fringe areas is generally reported to be of the order of 10 to 15 miles, while in the Gulf of Mexico and off the coast of the United States an accuracy of 5 to 10 miles is indicated in most

cases. The aircraft fixes near the coast of the United States, near the Bahamas, and in much of the Caribbean Sea are based on radar positions and an accuracy of 5 miles or better is claimed in many instances. In view of the difficulties of identifying the storm center and problems of radar interpretation discussed below, it is felt that the accuracy of actual hurricane fixes is considerably poorer than might be suggested by the data shown in figure 3.2.

## 3.3 Accuracy of Radar Fixes

### 3.3.1 Examples of Erratic Radar Positions

In a number of instances in recent years hurricanes have been tracked simultaneously by several radars and the reported instantaneous positions have often shown fairly large differences. This was pointed out as early as 1955, as illustrated by figure 3.3, but the most complete analysis of the differences in the reported positions is probably that made by Conover [6] for hurricane DONNA of 1960. An illustration from this study is presented as figure 3.4. During the first half of the track, shown in this figure, the positions reported by the Navy reconnaissance aircraft were generally to the north and east of those reported by the Miami Weather

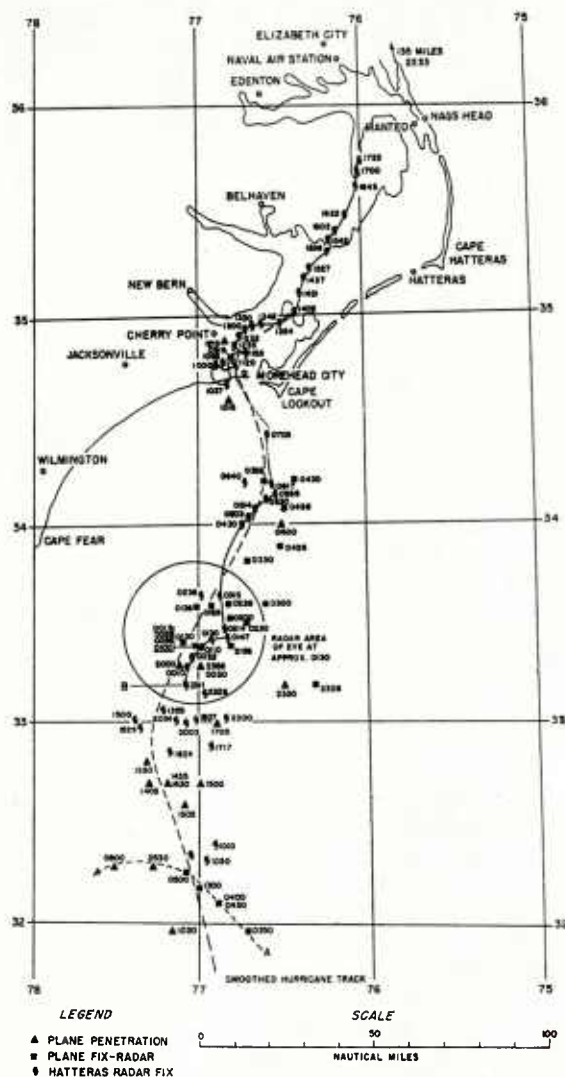


Figure 3.3. Fixes of the Center of Hurricane IONE, 1955; as Reported by the Hatteras Radar and by Aircraft Reconnaissance during the Period from 0330 GMT, 11 August Through 1725 GMT, 12 August. (From [11].)

Bureau radar, with several differences exceeding 20 miles; or, expressed in a different way, the maximum differences exceeded twice the eye diameter. The radar fixes from the University of Miami radar also tended to be to the north of those sent by the Miami Weather Bureau radar, with maximum differences approaching 15 miles. The differences in reported positions of the storm center at individual times, shown in figure 3.4, illustrate that even with very complete radar and reconnaissance coverage the tracking problem is not always simple. Some of the erratic features in the radar positions may be due to irregular motion of the storm center, and this topic is

taken up in the next section. However, there is no evidence in the data presented by Conover to suggest that the irregular features shown by one radar station could be verified by reference to data from other stations. Land observations in the Florida Keys gave considerable evidence that the actual track of DONNA was much smoother than indicated by the fixes from the Navy reconnaissance aircraft and that errors probably exceeded 20 miles on some observations.

Another case of rather erratic radar fixes occurred during hurricane AUDREY of 1957, even though an accuracy of 5 miles was specified for the fixes (fig. 3.5). In this case the observer indicated that the aircraft position was "positive" on all except the 0430 GMT observation which was listed as "good", and the center selection was indicated as "positive" or "good" on all except the 0300 GMT observation which was listed as "fair". It can be seen that if the actual positions were within the indicated 5-mile accuracy the storm center moved in a very erratic fashion, especially during the early part of the record.

The DONNA and AUDREY cases discussed above indicate that the radar fixes from reconnaissance aircraft are probably subject to somewhat larger errors than might be suggested by the data shown in figure 3.2. The DONNA data also show that agreement between fixes provided by nearby land-based radar stations leaves much to be desired. These cases may not be typical. Perhaps in many other instances the radar tracks of hurricanes will be much smoother, and a greater consistency will be found between fixes provided by several radar stations. On the other hand, the DONNA and AUDREY cases are not considered as extreme ones, and a search of the reconnaissance and radar files would probably reveal other cases in which the fixes were even more erratic. In the following paragraphs an attempt will be made to examine the factors which may be important in accounting for discrepancies of the type discussed above. Possible errors in the land-based radar observations will be taken up first and then the much more complicated problem of the airborne radar will be considered.

### 3.3.2 Land Based Radar

#### (a) Difficulties in Locating the Center of the Radar Eye

The structure of the core of hurricane DONNA was relatively simple as it approached the Florida Keys. The wall cloud surrounding

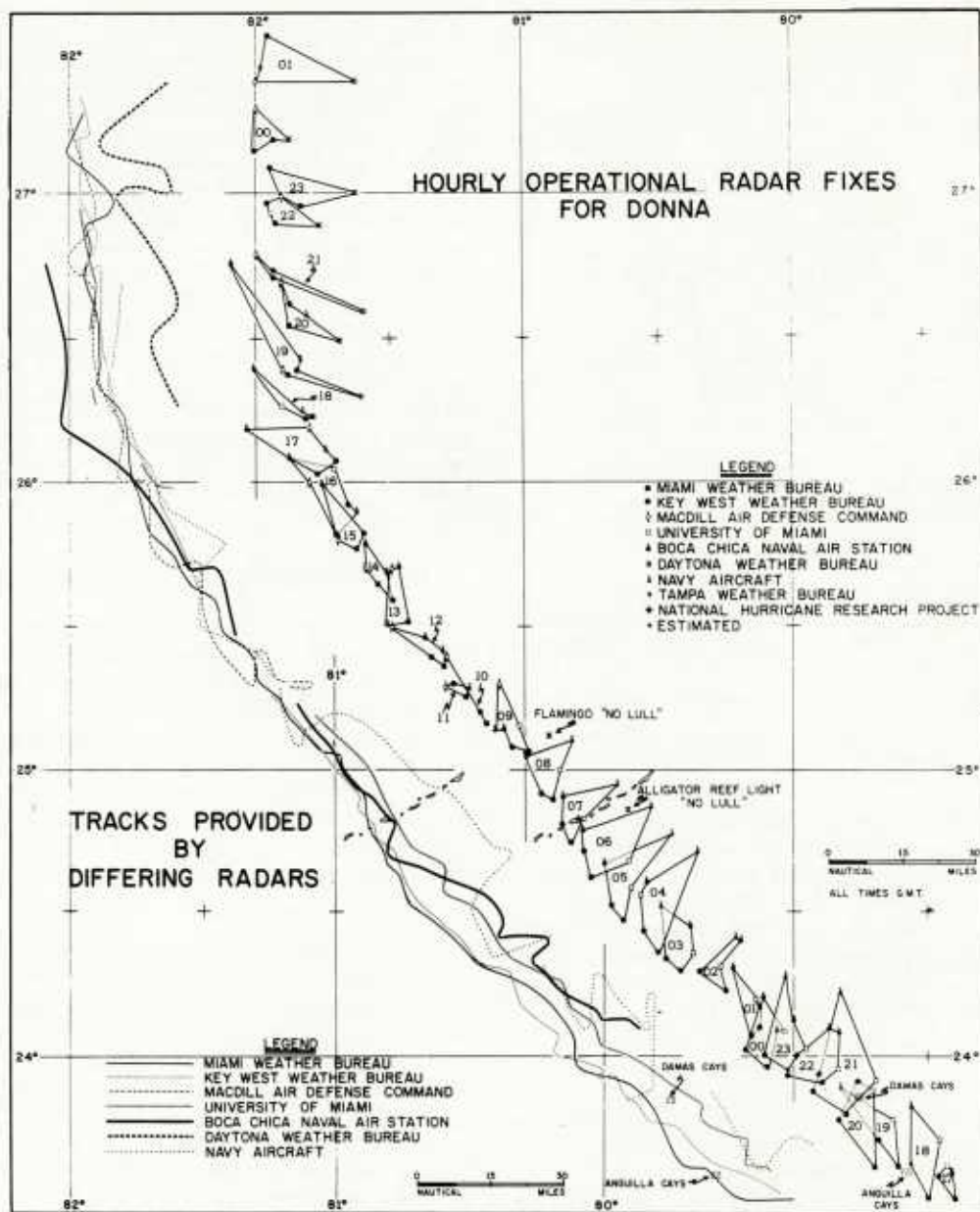


Figure 3.4. Hourly Operational Fixes of the Center of Hurricane DONNA on 9-10 September, 1960 as Provided by the Indicated Radars. Smoothed Tracks Determined from Successive Fixes at Individual Radars Are Shown on the Left Portion of the Figure. (From [6].)

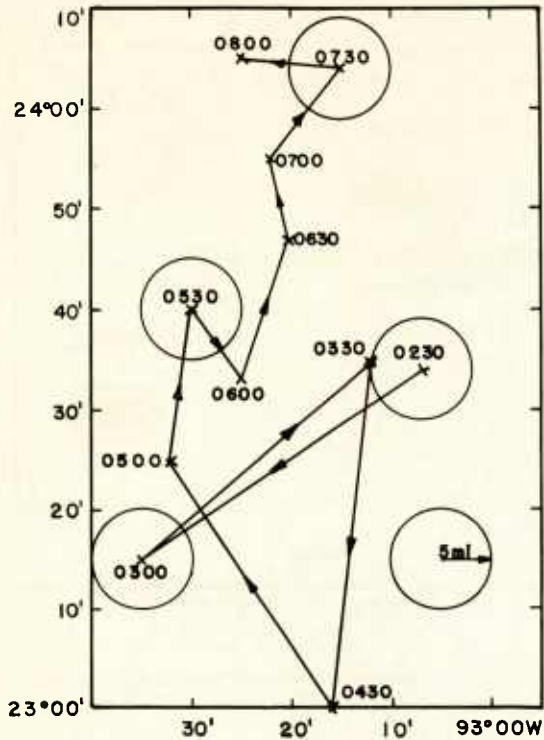


Figure 3.5. Successive Radar Fixes of the Center of Hurricane AUDREY as Reported by a U. S. Navy Reconnaissance Aircraft Have Been Connected by Line Segments from 0230 GMT through 0800 GMT, 26 June 1957.

the eye was well developed and completely encircled the eye, and there was no significant tilt of the eye with height. Even so, the eye undoubtedly appeared somewhat differently on the various radarscopes, and some of the differences noted above may have resulted from problems in center selection. The sensitivity of the radar set, the local propagation conditions, and the attenuation of the radar energy by the heavy precipitation in the storm core may all have been factors contributing to difficulties in center selection. Although center selection difficulties may have existed, it would seem that they should have been relatively minor during this portion of the life of DONNA, at least in comparison with those present in weak and poorly developed hurricanes.

#### (b) Range and Azimuth Errors

Differences in the reported geographic positions of clearly distinguishable radar features, as observed by different radar stations, may be due to range and azimuth errors in the radar systems as well as to various types of observing and recording errors. Conover [6] suggested that errors of both types were present in the

observations from hurricane DONNA and showed that some of the systematic errors in azimuth, due to improper calibration or alignment, were quite large.

Azimuth errors, due to refraction of the radar beam by horizontal gradients in the refractive index, are possible but it is unlikely that any bending effect of this type would exceed the maximum vertical bending, which is probably less than  $1^\circ$  in all cases [38]. Therefore, this effect would generally be small compared to uncertainties in the azimuth orientation, which is probably of the order of  $1^\circ$  under the best of conditions [6]. Some of the differences between the various land-based radar observations are such as to require range errors in excess of 10 miles and azimuth errors in excess of  $5^\circ$ . The systematic features observed in some of the cases clearly suggest that the differences can hardly be explained by observer error, unless some problem of interpretation of the center position were involved.

#### (c) Charting Errors

Some uncertainty can result from positioning the storm center geographically from range and bearing data, especially if nonconformal map projections are used. However, even at ranges of 200 miles, errors of this type would probably not exceed 3 miles on the types of charts normally used for meteorological purposes. Actually, errors in the position of stations and land features on the charts are probably more important than the use of nonconformal projections.

It is probably the combined effect of the several types of errors mentioned above which give rise to the previously discussed differences in center fixes from land-based radar. Perhaps the differences could be reduced appreciably by more complete and frequent calibration and alignment checks. It is doubtful, however, that completely consistent results could be obtained from two carefully calibrated radars of the same type located even a few miles apart.

#### 3.3.3 Airborne Radar

In the case of the land-based radar the position of the radar and its orientation should be closely known. This is not necessarily the case for airborne radar since fairly large navigation errors may be present at times, and the north direction given by the magnetic compass may be somewhat in error even after correcting for the magnetic variation. Local anomalies in the

magnetic variation as well as errors in the aircraft compass calibration probably lead to errors in excess of  $2^\circ$  in some instances. Whenever possible, hurricane positions are determined by measuring range and bearing from clearly distinguishable land features rather than relative to the position of the aircraft. If several well-defined land features are shown on the scope, ranges are measured from these features and arcs are swung on a map to determine the geographical position of the center. If this procedure can be used, azimuth is not used, and errors in north orientation are immaterial. However, in many cases when several land targets are available the arcs do not intersect at a point. The "circle" of uncertainty can be quite large and this was the case of hurricane DONNA as it approached the Florida Keys. Rather well-defined radar presentations of the lower Florida east coast, the Florida Keys, the north coast of Cuba, and Andros Island were obtained but, even so, the uncertainty was often of the order of 10 to 20 miles. There are at least two factors in explaining this difficulty. The first, discussed below, is due to the distortion of the radar presentation of land areas due to the width of the radar beam and the second is due to "changes in the coast lines" due to the storm.

#### (a) Beam Width Distortion

The beam width distortion is illustrated schematically by figure 3.6. The actual island shape is shown solid, and the increase in area which might appear on the radar presentation is shown by the hatched portion. The return from only a portion of the beam may be great enough to give an echo on the radarscope and this will, of course, be presented at the azimuth corresponding to the center of the beam at that instant. Therefore, island A which is elongated in the tangential direction, relative to arcs about the radar, will tend to be elongated even more as shown by the hatched area. Island B, because of its radial orientation relative to the radar, would tend to be broadened. Pulse length effects would tend to offer distortions in the opposite sense on the back sides of the islands but these would be quite small compared to the beam width distortion [3]. Because of the possibility of distortion of land targets, the observer should be quite careful in the selection of points to be used. For a radar return of the shape illustrated by C (fig. 3.6) point x would be a much better reference than point y, since the island would tend to be stretched in the tangential direction. The point of land ending at x would be broadened but the tip should appear at the correct azimuth

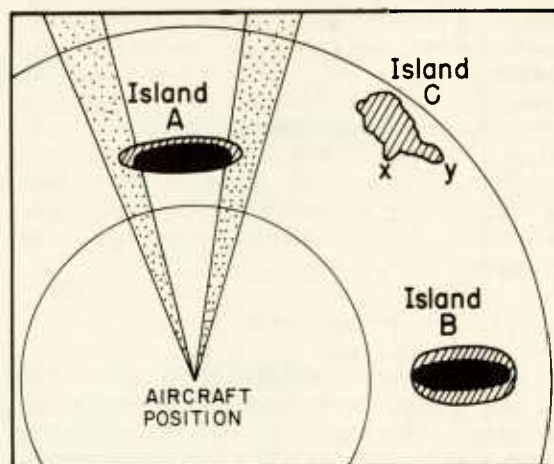


Figure 3.6. An Illustration of the Distortion of Radar Targets Due to the Width of the Radar Beam.

and range. The magnitude of errors of this type will depend upon the beam width of the radar and the range from the target.

As mentioned previously, the horizontal beam width of the APS-20E radar used on the Navy reconnaissance aircraft is about  $1.5^\circ$ . If sharp-edged beams were actually produced by the antenna, the maximum errors due to the beam width effect, corresponding to one-half the beam width, would exceed 2 miles only at ranges in excess of 150 miles. However, side lobe return may be present in some cases, especially at short ranges, and greater distortion may be present. The horizontal beam width of most airborne radars is somewhat larger than that of the APS-20E and the possible error is, therefore, a little greater. However, most airborne radars operate in the x-band and are of very limited use in the long-range tracking of hurricanes because of the severe attenuation which results from the heavy precipitation near the storm core.

#### (b) Changes in the Coastline

The changes in sea level due to the effects of a major hurricane may be such as to change the coastline by several miles, especially in some low swampy areas such as southwestern Florida and southwestern Louisiana. Conover [6] mentions the possibility that changes in the coastline due to the evacuation of the water from Florida Bay and the piling up of water along the south Florida coast may have contributed to some

of the poor fixes reported by the Navy reconnaissance early on September 10 (fig. 3.4). There is also the possibility that heavy seas breaking over reefs may be interpreted as ground return and as a result certain peninsulas and prominent features of islands may appear to be extended on the radar during strong wind conditions. Similarly, heavy breakers in shallow water, such as occurred along the north coast of Cuba during hurricane DONNA, may have made it more difficult to clearly distinguish the coastline.

#### (c) Echo Interpretation

Another problem which is always present in the use of radar for navigation purposes is that of weather echoes in the vicinity of land targets which may be interpreted as part of the ground return. For example, a line of showers along the southwestward extending point on island C (fig. 3.6) might extend beyond point x and its end might be misinterpreted as the limit of the land. Difficulties of this type are probably relatively unimportant at ranges up to 50 to 75 miles.

#### (d) Navigation Errors

The most difficult problems in radar tracking of tropical cyclones occur when the storms are far out to sea and positioning must be relative to the aircraft. For example, in the area east of 55° W. (fig. 3.2) the navigation fixes are seldom considered more accurate than 20 miles. In some cases land targets as much as 300 miles from the storm center may be used for radar fixes if the aircraft is roughly half way between the land and the storm center. However, at a range of 300 miles a compass error of 2° would result in a position error in excess

of 10 miles and, of course, the problems of center selection increases with range from the storm center.

### 3.4 Irregularities in the Tracks of Tropical Cyclones

Over the remote oceanic areas tropical cyclones are usually tracked from one or two fixes per day and the plotted storm tracks are normally quite smooth. As the storms move into areas where several fixes per day are available, the indicated storm tracks become much more irregular. As discussed previously, these irregularities become even more prominent as the storms approach land areas where frequent reports from several land-based radars may be available in addition to the reconnaissance observations. The hurricane forecaster is continually plagued by the irregularities of the storm motion as indicated by the frequent fixes, and it is apparent that many of the short period indications are worthless in forecasting the motion of the storm over a period of even a few hours. There is little doubt that in many cases the irregularities are due to errors in the fixes but in other instances they probably indicate quite closely the actual track of the storm center. These irregularities are smoothed out in most operational work but there is always the question of whether useful information is being lost by ignoring the details. This section will be concerned primarily with the evidence which has been presented in the literature in support of regular and irregular deviations from smooth tracks and in assessing the practical importance of these features.

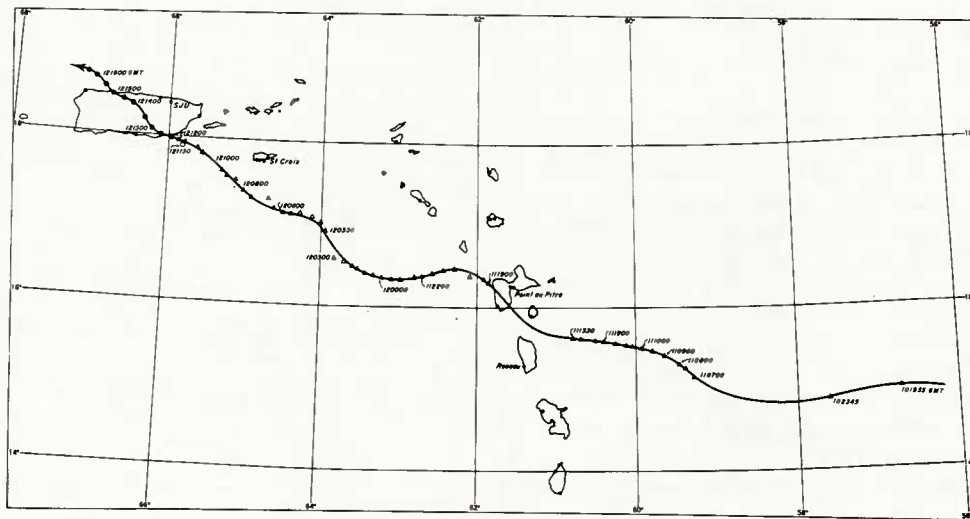
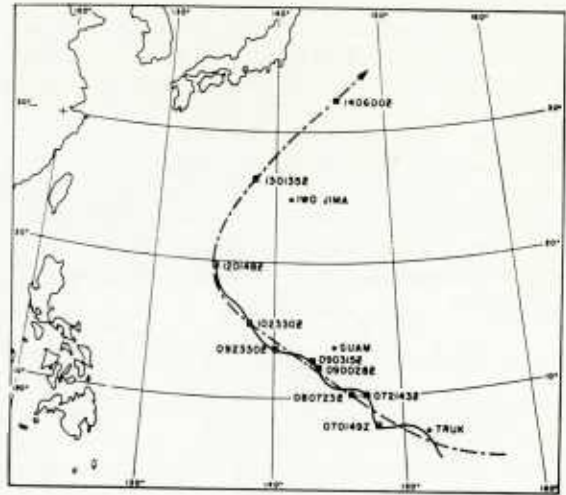
#### 3.4.1 Periodic Large Scale Oscillations

Theoretical work by Yeh [39] suggested that



Figure 3.7. Examples of Oscillatory Paths of Two 1947 Hurricanes. Date and Time Are Shown at Six of 12-hour Intervals Along the Tracks (From [ 39 ] ).

In recent years, fixes have often been much more frequent and deviations from smooth tracks have been noted in many tropical cyclones, but these seldom suggest a periodic oscillation in the storm motion. Perhaps the best cases of oscillatory motion which have been discussed in the literature in recent years are those presented in figures 3.9 and 3.10. The track of hurricane BETSY of 1956 (fig. 3.9) suggests an oscillation with an amplitude of 10 to 15 miles and a period of 7 to 12 hours. In the case of hurricane CARLA (fig. 3.11) the amplitude was about 10 miles and the period was about 6 to 8 hours.



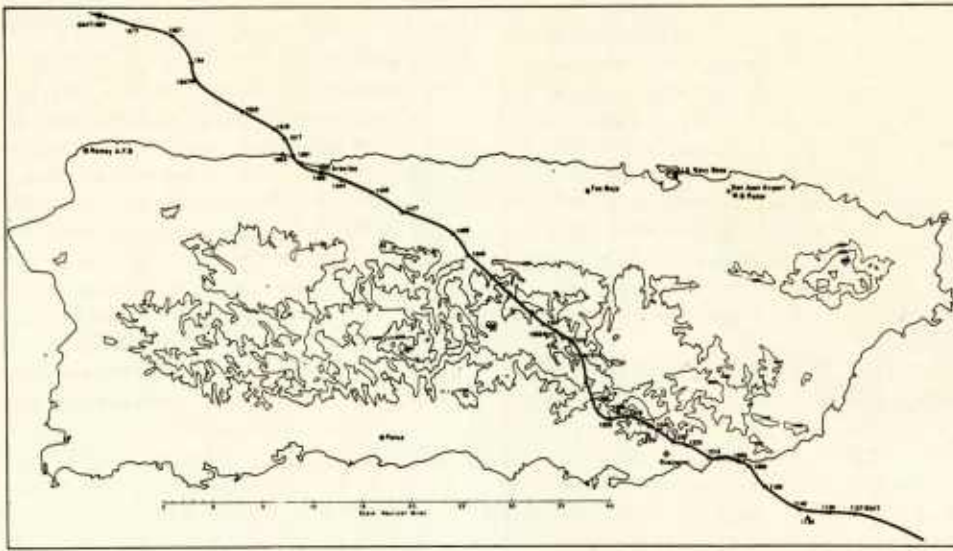


Figure 3.10. The Track of Hurricane BETSY on 12 August 1956 as Determined by Fixes from the U.S. Weather Bureau SP1M Radar at San Juan, Puerto Rico. Times Are to the Nearest Minute (From [ 5 ] ).

It is interesting that the oscillations in CARLA resemble a trochoid<sup>1</sup> which is the form predicted by the theoretical work of Yeh [39].<sup>2</sup>

### 3.4.2 Nonperiodic Large Scale Irregularities

In many instances irregularities in the storm tracks are noted which do not appear to be periodic. The oscillations shown for hurricane BETSY (fig. 3.9) tended to damp out as the storm approached Puerto Rico, but smaller scale deviations from a smooth track were noted as the storm was tracked across the island by radar (fig. 3.10). Even more irregular motion is often noted, as illustrated by the track of hurricane IONE of 1955 (fig. 3.12). The small loops indicated deviations from a smooth track of less than 10 miles but, on a somewhat larger scale, there is a suggestion from this track of a trochoidal oscillation with a period in excess of 12 hours.

Oscillations on the scale shown in figure 3.11 and 3.12 can usually be detected only from a series of positions reported by an individual radar station. If all available fixes are plotted on a single chart, as illustrated by figure 3.3, the position of the storm center appears to jump around in a rather haphazard manner.

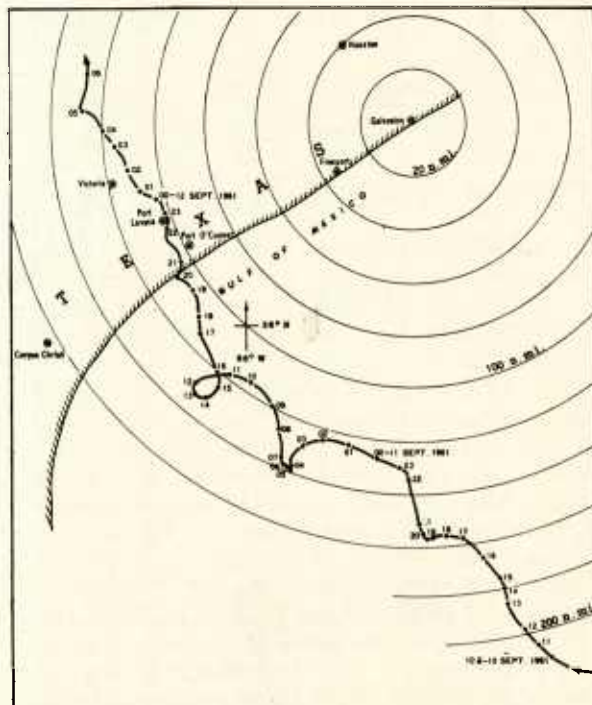


Figure 3.11. The Track of Hurricane CARLA on 10-12 September 1961 Based on Hourly Radar Fixes from the U. S. Weather Bureau WSR-57 Radar at Galveston, Texas (From [ 2 ] ).

<sup>1</sup> A curve generated on a plane by a point on the radius of a circle (in the same plane) as it rolls, without slipping, in a straight line.

<sup>2</sup> Note that the amplitude and period of the oscillations are not consistent with other parameters when used in Yeh's equations.

### 3.4.4 Causes and Effects of Track Irregularities

The irregularities in the tracks of tropical cyclones discussed above ranged from periodic oscillations extending over intervals of the order of 2 days down to nearly random fluctuations over periods of much less than 1 hour. Some of the apparent deviations from a smooth track undoubtedly arise from position errors and from the difficulties in defining the storm center. However, there is little doubt that small-scale fluctuations are probably present in many cases. Features of the type shown in figures 3.11, 3.12, 3.13, and 3.14 suggest that observations taken at intervals much less than an hour apart are of little value in indicating the future motion of the storm during the following 3 to 6 hours. Similarly, observations made at intervals of a few hours are of limited use in indicating storm motion over periods of 12 to 24 hours. Therefore, even extremely accurate tracking of the center of tropical cyclones may be of little value for forecasting purposes. In fact, it may prove desirable for the radar stations to prepare detailed tracks of the type shown in figures 3.13 and 3.14 and send positions corresponding to the mean track obtained after removing the small irregularities.

The smaller-scale fluctuations in center position, and perhaps even those of the type shown in figures 3.11 and 3.12, are probably not accompanied by similar variations in the course of the storm as a whole. Of course, it is difficult to define the "whole storm" since there is little information on such parameters as the extent of the hurricane force or gale-force winds



Figure 3.12. Apparent Track of Hurricane IONE on 18-20 September 1955 as Determined from Fixes from the Hatteras Radar. Times Given Are in Eastern Standard Time (From [ 23 ] ).

### 3.4.3 Small Scale Fluctuations

Attempts have been made to examine even smaller scale irregularities than those presented in figures 3.11 and 3.12 from careful evaluation of radar films. Senn [32] described irregularities in the tracks of hurricane DEBRA of 1959 and DONNA of 1960 based on radar fixes made at 5-minute intervals (figs. 3.13 and 3.14). These small-scale fluctuations in DONNA occurred during a period when the synoptic scale track was relatively smooth, but hurricane DEBRA was moving quite slowly during the time of the irregularities. The reality of these features is open to doubt in view of their small amplitude. In the case of DONNA the indicated amplitude was of the order of 1 mile, and these small fluctuations were observed at a range of about 100 miles. Even if the center could be selected with an accuracy much greater than 1 mile, variable azimuth errors of less than 1°, due perhaps to wind loading on the antenna, could account for a large part of the deviations from a smooth track.

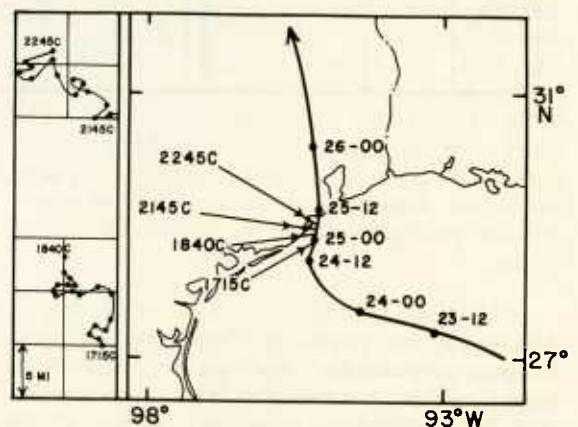


Figure 3.13. The Track of Hurricane DEBRA on 23-26 July 1959. The Insets Show the Detailed Track of the Storm Center Over the Indicated Short Periods (1715 to 1840 CST and 2145 to 2245 CST 24 July) as Obtained from 5-Minute Fixes from the CPS-9 at College Station, Texas. Both Insets Are on the Same Scale. (The Insets Were Taken from Figures Prepared by Senn [ 32 ].)

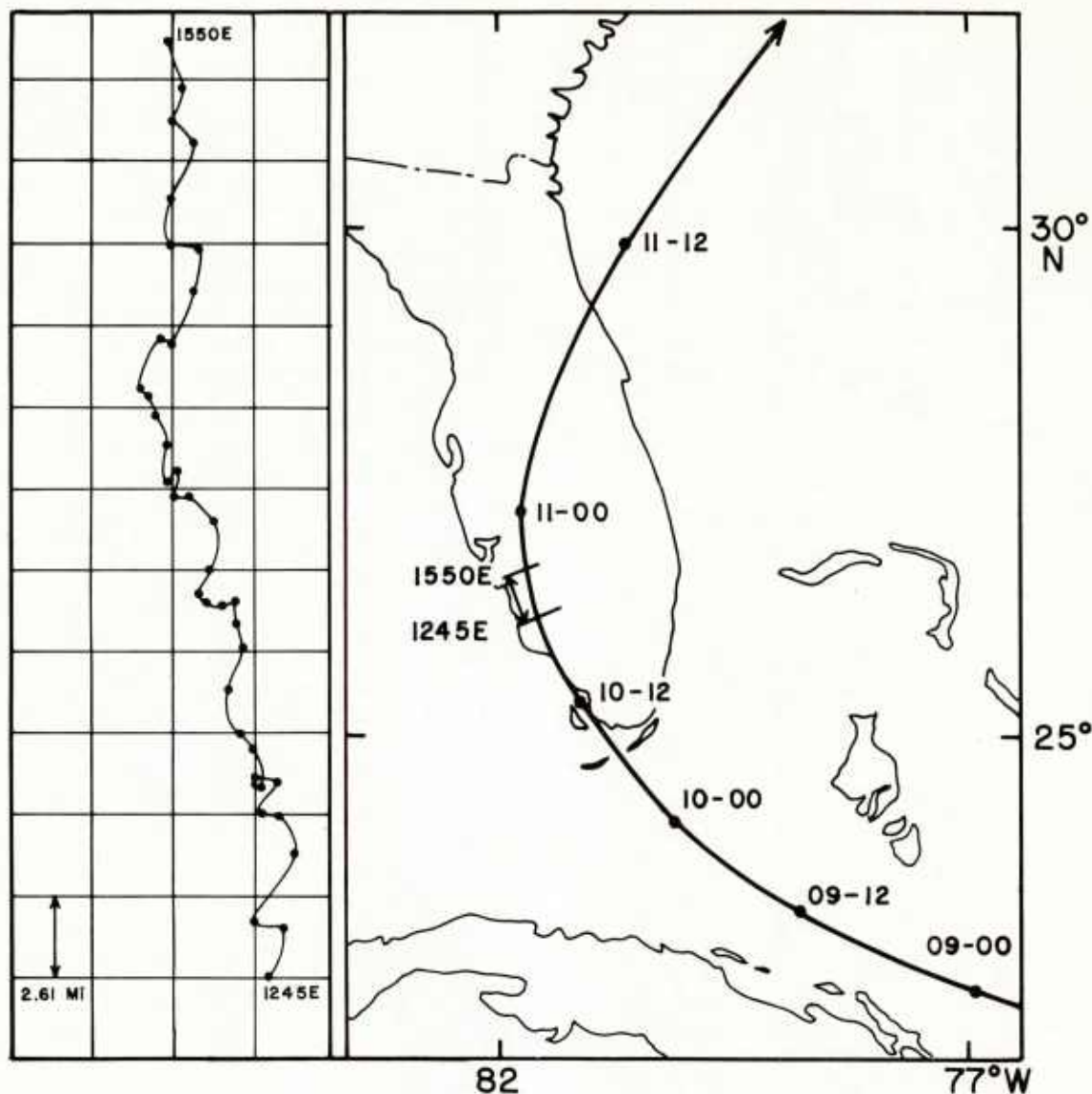


Figure 3.14. The Track of Hurricane DONNA on 9-11 September 1960. The Left Hand Portion of the Figure Shows the Detailed Track of the Storm Center Over the Period 1245 to 1550 EST, 10 September as Determined from 5-Minute Radar Fixes from the SPIM Radar at the University of Miami. (This Detailed Track Was Taken from a Figure Presented by Senn [32].)

in the various sectors of the storm. There is little reason to think that the centroid of the envelope of hurricane-force winds, or any other similar parameter, would move in exactly the same way as the geometrical center of the radar eye.

The radar presentations suggest that the small-scale irregularities in the track of the center may be due to the character of the ra-

dar features in the extreme inner portion of the storm. In cases such as shown in figure 2.4, the ring-like echo may tend to oscillate back and forth across the mean path of the storm due perhaps to asymmetries in the wind field. In other cases the eye structure is subject to considerable change in size and shape over periods of an hour or less. These changes seldom affect all sectors in the same way; more often one part of the eye wall will strengthen or weaken in a

short period of time. Following a change of this type the eye may go through a period of adjust-

ment of an hour or longer before resuming a stable pattern.

#### 4. CONCLUSIONS

In the first part of this report considerable time was spent on the problems involved in specifying the center of a tropical cyclone for tracking purposes, and it was argued that the center can usually be specified much more objectively from radar observations than by other means. However, the evidence presented in the last section suggests that the radar center positions may be subject to fluctuations which do not reflect the motion of the storm as a whole. Any other type of center position would undoubtedly have the same deficiency. The features in the storm track due to the irregular motion of the radar center, as well as those due to errors in the fixes, impose limitations on the accuracy

with which tropical cyclones can be tracked. Although some improvement can be expected in the future, this irregular motion appears to be a type of uncertainty which can not be entirely removed, and as a result there is probably some limit on the accuracy which can be attained in storm tracking. A complete modification of our concept of storm tracking away from the center position approach, which might involve parameters aimed at describing the storm as a whole, does not appear practical at the present time. A much expanded program of wind and/or pressure-height observations throughout the storm circulation would appear necessary for any attempt of this type.

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